RURAL TECHNOLOGY

Edited by
AMULYA KUMAR N. REDDY

INDIAN ACADEMY OF SCIENCES
Bangalore 560 080

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Foreword

Although problems of rural relevance are intimately connected with the lives of three-quarters of the world's population, they have been conventionally viewed as being outside the mainstream of international science and technology. This monograph, which is a collection of papers devoted to the theme of *Rural Technology* and published in the March, September and December 1979 issues of the Proceedings of the Indian Academy of Sciences (Section C: Engineering Sciences), is perhaps the first attempt to treat such problems as legitimate concerns for serious engineering science. It is necessary, therefore, to outline the perspective within which these papers must be seen.

For at least two centuries, and particularly during the first half of this century, science and technology were pursued as unmitigated blessings. This unquestioning belief was first shaken by the explosion of the atomic bomb and the subsequent proliferation of nuclear weapons. Further, what was viewed by some in the late forties and early fifties as an unfortunate aberration of science and technology came to be perceived by many in the sixties as its normal character. The perception changed primarily because of the numerous instances of reckless depletion of the earth's non-renewable resources and of near-permanent damage to the environment. The result was the growth of an anti-science and anti-technology movement among the youth, precisely in those countries where science and technology were most advanced.

But, this negative approach appears naive and futile in the light of the experience of the developing countries. There, another judgement on science and technology gathered strength. In the years after World War II, science and technology had become increasingly preoccupied with the satisfaction of the demands of the affluent, in the industrialised as well as in the backward countries, and with the development of the military hardware necessary to protect this affluence. As a consequence, the bulk of humanity has not fully enjoyed the benefits of science and technology, and still ekes out its life in abysmal poverty and squalor. The set of traditional technologies, which this section of humanity had evolved over the centuries, and depended upon for its survival, has become increasingly inadequate in the context of rising expectations, changed circumstances, proliferating populations and depleting resources. At the same time, the technologies of the industrialised countries seem to have become too demanding in their use of capital, energy, and non-renewable resources to become available to all sections of humanity—they appear to be inherently exclusive. This situation, in which the traditional is invariably inadequate and the modern is largely inaccessible, can only be overcome by the proliferation of alternative solutions through massive inputs of science and technology. Hence, for the vast millions of Asia, Africa and Latin America, the hope lies, not in a rejection of science and technology, but in its radical reorientation.

It has been argued elsewhere (Reddy 1979) that the guidelines for this new direction must emerge from the concept of *development* as a process directed towards

(i) the satisfaction of basic needs, starting from the needs of the neediest,
(ii) an endogenous self-reliance based on social participation, and
(iii) harmony with the environment to ensure the sustainability of this development.

This view implies a rejection of the equation 'development equals growth', an emphasis on man and the quality of life rather than on things and the quantity of goods and services, and a scrutiny of the distribution of the benefits of growth rather than its magnitude only. It also implies a conscious search for those alternatives which advance development without degrading the environment.

If this objective of a need-based, self-reliant, participatory, environmentally-sound development is to guide the reorientation of science and technology, it is suggested that several fundamental changes in attitudes become necessary (Reddy 1978). However, this is neither the vehicle nor the occasion to discuss such general issues which are inevitably controversial. What needs to be mentioned here is that there are already signs of such changes having begun. Attempts, however insignificant they may be on a global scale, are being made, both in the developed and developing countries, to promote a re-orientation of science and technology.

The papers of Taylor from Princeton, Fraenkel from London, Kannan from Trivandrum and of Popali, Yardi and Jain from Baroda are indications of such a world-wide movement in its embryonic stages. It was only the limitation of awareness and association which prevented contributions from many other centres being included here. Thus, no significance, other than the coincidence of proximity and collaboration, must be attached to the fact that most of the papers in this monograph originate from a group of faculty at the Indian Institute of Science, Bangalore, which in August 1974 formed a cell for the Application of Science and Technology to Rural Areas which is now more widely known by its acronym ASTRA (meaning 'weapon' in Sanskrit).

The purpose here is to present the first fruits of the work inspired by the new concerns.

Most of the papers on *Rural Technology* in this monograph are concerned with energy. This bias is not intended to underrate the importance of problems in the area of agriculture, health, education, rural industries, etc.; it is only a reflection of the interests of the individuals and groups involved with this contribution. Future collections of papers on the same theme, irrespective of where they are published, may have a totally different assembly of subjects. Thus, these papers merely initiate the theme of *Rural Technology*.

Nevertheless, it is suggested that several important conclusions emerge from this set of papers. Firstly, the problems tackled appear quite mundane, but they are certainly not trivial. Secondly, they demand the same rigour, sophistication, subtlety and creativity as is generally associated with the technologies of the industrialised countries. From this point of view, the labelling of rural technologies as 'low' or 'primitive', in contrast to industrialised country technologies which are designated as 'high' or 'advanced', represents a confusion over criteria—the criterion of high/low or advanced/primitive should be based on the quality of scientific and engineering thinking underlying a technology, and not on its scale or its geographical origin. Thirdly, the necessity of first understanding needs before defining what technologies are required implies the vital importance of surveys and studies of the rural scene as it is today, before development-oriented intervention is attempted. Hence, a grassroots understanding of rural areas to identify problems and define them precisely

is perhaps the most important step in solving the technical component of rural problems.

It remains to mention that, in almost every case, the papers in this monograph represent exploratory contributions on matters which have been rarely analysed in detail. Their primary purpose is to raise questions and open up lines of work, and thereby stimulate wider awareness of these problems and attract more investigations. It has also been the intention to demonstrate that problems of rural relevance can be as scientifically challenging, intellectually stimulating and professionally satisfying as other concerns of engineering science. If the papers succeed in these tasks, the work reported here would have amply served its purpose.

AMULYA KUMAR N REDDY
Guest Editor

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Hills, dams and forests. Some field observations from the Western Ghats

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Abstract. Man's attempts to intensify the use of natural resources can often result in the exhaustion of the resource or deterioration of other interacting resources. The single-minded pursuit of the development of the water resources of the rivers of the Western Ghats shows many examples of this view, particularly in the unnecessary destruction of the dwindling forest resources. This destruction may be caused by (i) problems of rehabilitation, e.g. the Ramanagar settlement of the Kalinadi project (ii) the impact of labourers, e.g. the destruction of evergreen sholas on the Upper Nilgiri plateau (iii) the access to encroachers and poachers, e.g. Panshet and Kalinadi (iv) faulty planning, e.g. Linganamakki and Kalinadi. This destruction of forest cover has had a number of deleterious consequences in (i) worsening the shortages of forest resources, (ii) hastening the siltation of the reservoirs, (iii) ecological imbalances as in the rapid spread of *Eupatorium* in the Kalinadi project area and (iv) the decimation of biological diversity, as in the great reduction of evergreen forests in the Western Ghats, threatening the survival of lion-tailed macaque and the extinction of grass species, *Hubbardia heptaneuron.* It is stressed that the only sustainable and therefore true development is environmentally sound development. The interests of the weaker sections of the society often provide a good index of the soundness of the development from an environmental point of view. The planning of the development process with this perspective is a great scientific and technological challenge that must be taken up.

Keywords. Environmental impact; rehabilitation; deforestation; dams; hydroelectric projects; irrigation projects.

1. Introduction

A more intensive utilisation of the natural resources of the earth has underlain all economic development. Thus domestication of animals has concentrated the more dispersed populations of wild animals used by the hunter-gatherers, and irrigation has enhanced the supply of water to cultivated crops in previously rain-fed tracts. The natural resources of the earth are however finite and often interdependent. An intensification of the utilisation of one such resource can therefore lead to its exhaustion, even if it is a renewable resource, or to the deterioration of another interacting resource. It is now well known that historically an intensification of resource use has often resulted in its exhaustion and in many undesirable side effects with a consequent deterioration of the quality of human life (Thomas 1956). Although modern-day technology has enhanced by several orders of magnitude man's ability to use the earth's natural resources, it has not overcome the traditional problems of over-exploitation and of the deleterious impact on other natural resources. As a matter of fact, the magnitude of these problems has often become proportionately greater.

Farvar & Milton (1973) document a number of such consequences of what they term 'careless technology,' ranging from the outbreak of schistosomiasis following the construction of the Aswan dam in Egypt to the salinisation of large tracts of farmland following intensive irrigation in the Indus basin in Pakistan.

The ancient land of India abounds in many such examples, beginning perhaps with the man-induced desertification of Rajasthan (Bryson & Barreis 1967). This vital problem has however received scant attention in our country, and the major global reviews of Thomas (1956) and Farvar & Milton (1973) contain no significant material on India. Symptomatic of the near-total lack of our understanding of this problem is the fact that the exhaustive treatment by Rao (1975) of the water wealth of India and its utilisation makes only a passing reference to the environmental problems attendant on such utilisation.

The present paper is therefore a preliminary attempt at documenting a few specific aspects of the environmental consequences of the intensification of the utilisation of India's natural resources. In this paper, attention is focussed on the use of river waters through the construction of reservoirs on the Western Ghats in Peninsular India. The orography of the Western Ghats interacting with the winds of the south-west monsoon leads to the highest levels of precipitation for Peninsular India on the crestline of the Western Ghats. This heavy precipitation, coupled with the steep westward slopes of the Ghats renders this an ideal location for the generation of hydroelectric power, and many such projects, e.g. Koyna, Linganamakki, Upper Bhavani and Idikki, have been completed on this hill chain. The major eastward flowing rivers of Peninsular India—Godavari, Krishna and Kaveri all originate on the Western Ghats and the region where the hills of the Ghats merge with the Deccan Plateau furnishes ideal conditions for the construction of irrigation projects, and many such, e.g. Panshet, Kabini and Bhawanisagar, have been completed in recent years.

As has been the world-wide experience, these projects have tended to focus entirely on the construction of dams, canals, tunnels, pipelines and power-generating stations, with little attention to the other wide-ranging consequences of the projects (Farvar & Milton 1973; Dasmann *et al* 1973). The Western Ghats today harbour almost the entire forest wealth of the states of Gujarat, Maharashtra, Goa, Karnataka, Tamilnadu and Kerala, and these forest resources are already seriously in short supply (Gadgil & Prasad 1978). Moreover, the irrigation and hydroelectric projects have led to serious deforestation not just in the submersion areas, but in the vital catchment areas as well. This in turn has enhanced the soil erosion in the catchment and siltation of the reservoirs. It has sharply reduced the diversity of plant and animal life of this region, and has led to ecological disturbances. All of this has serious long-range economic consequences for the society as a whole, but its more immediate victims are the tribals and peasants of the Western Ghats (Darwin 1976; Anon 1977a).

These developments have received little systematic attention, apart from some references in the report of the Task Force (Anon 1977a) and two studies on the Kuttanad and Silent Valley projects (Kannan 1979; Prasad *et al* 1979). An attempt is made in this paper to document these developments with particular reference to loss of forest resources on the basis of the author's observations during the course of field work in various regions of the Western Ghats beginning in early 1972 (Gadgil and Vartak 1976; Prasad & Gadgil 1977; Sastri *et al* 1977). The material

presented here was incidental to the primary objectives of these studies, though it interested the author greatly from the very beginning. It could not however be collected as systematically and with as careful a quantification as one would have wished, for my understanding of the problem has unfolded only gradually. At this juncture, therefore, the material presented is only a preliminary statement which aims to define the problem, illustrate some of its aspects and suggest lines along which more careful and quantitative studies ought to be carried out.

Let us begin by presenting a case study, that of the Panshet reservoir in Pune district in somewhat greater detail to illustrate the various forces at play. The various factors directly or indirectly associated with dams which lead to a destruction of vegetation cover are then considered. This will be followed by an examination of the adverse consequences of this destruction, for the society in general, and for its weaker sections in particular.

2. Impact of the Panshet Dam

The Panshet reservoir is situated about 25 km to the west of Pune and has been created by the construction of dams on the rivers Mula and Mose (figure 1). The reservoir lies just to the east of the crestline of the Western Ghats at an altitude of about 600 m. The terrain is very much broken with narrow valleys of less than half

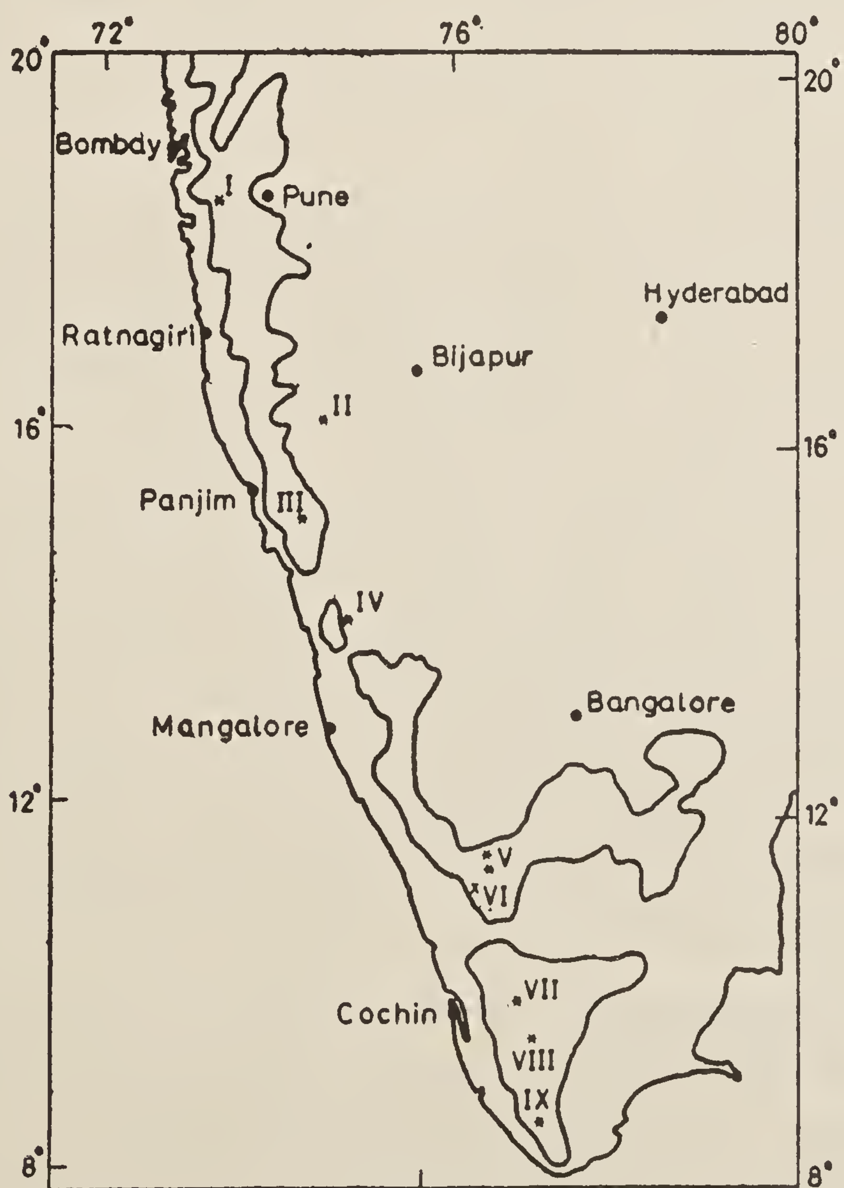

Figure 1. A map of Peninsular India showing locations of various sites referred to in the text.
I. Panshet, II. Hidkal, III. Kalinadi, IV. Linganamakki, V. Upper Nilgiri Plateau, VI. Silent valley, VII. Idikki, VIII. Periyar, IX. Mundanthurai-Kalakad

a kilometre in extent separated by steep hills rising to altitudes of around 1200 m. Before the construction of the reservoir, the peasants of this region grew paddy in the valleys and practiced shifting cultivation for millets on the lower hill slopes. These hill slopes had a good tree cover of mango (*Mangifera indica*) and harada (*Terminalia chebula*), for these cash-yielding trees used to be spared by the peasants while clearing for millet cultivation. The nuts of harada used extensively for tanning supported a flourishing industry at Bhor, some 50 km away. The upper hill slopes were clothed by a rich natural forest of the semi-evergreen type, constituted into state-owned forest reserves. These forests were hardly exploited due to the lack of transport facilities (Gadgil & Vartak 1976).

The work on the Panshet reservoir commenced around 1955 with the construction of a good road linking this region to the city of Pune. The submersion region consisting of the valleys with the paddy fields and the lowermost hill slopes with mango and harada trees had to be deforested. There was a great demand from the city of Pune for the excellent charcoal that can be prepared from the harada trees. Consequently, not only the submersion area but the entire lower hill slopes constituting over half of the catchment area was denuded of tree cover by 1960 (figure 2, plate 1). Apparently this occurred because the timber merchants who came in to deforest the submersion area bought the trees on the large tracts of private lands on the hill slopes at throw-away prices by convincing the peasants that they were soon going to be resettled far away in the command area of the dam, and that it would be in their best interest to sell off the trees. Be that as it may, the process of resettlement began only in the 1970s, a decade after this large-scale deforestation, and even today in 1979, only a minority of the peasants have moved to the new area, the rest continuing to live on the hill slopes.

With the deforestation of the hill slopes, the top soil has eroded rapidly in the face of the heavy annual precipitation of over 4000 mm, leading to large landslides by the early 1970s. This has depressed the productivity of the shifting cultivation, and consequently, the peasants have made large-scale encroachments in the reserved forest lands on the upper hill slopes for cultivation. The rich wild life including sambar, barking deer and wild pig that these hill slopes once harboured has all but disappeared with the destruction of the tree cover and the greater accessibility of the region to the well-equipped urban poacher. The peasants report that where they used to get a wild pig or deer once a week, they now hardly get a blacknaped hare once a month. With the disappearance of harada trees the regular cash income of the peasants has vanished and the harada-based industry at Bhor has been closed down. The very low amount realised by peasants through the sale of trees has been exhausted long ago. Although no data on siltation rates for Panshet are available, one has to merely see the eroded slopes and landslides to be convinced that they must be very high indeed.

It is evident that this devastation of the catchment, which in turn has led to the pauperisation of the inhabitants, the collapse of a forest-based industry, and siltation of the dam could have been forestalled if adequate measures to conserve the vegetation cover of the catchment were an integral part of the irrigation project.

3. Causes of deforestation

The execution of an irrigation or a hydroelectric project need involve the loss of forest resources only in the submersion areas. Apart from this, the creation of a large water body could positively help the other existing forest and wild life. The nearly century-old reservoir on the Periyar river in the heart of the Thekkady wild life sanctuary provides an example of this possibility (figure 1). In the case of this reservoir, not even the submersion area was deforested and the ancient tree stumps stick out of the water to this date, providing excellent perches for the rich bird life of the area. The wild life too has benefitted from the provision of a large perennial water body. The forest cover in the vicinity has also been fairly well preserved. Unfortunately, it is not possible to cite such examples from more recent times, where almost all projects seem to have had a devastating effect on the surrounding forest resources in a number of ways. These may be classified as problems of (i) rehabilitation (ii) labourers (iii) access to encroachers and poachers and (iv) faulty planning.

3.1. *Rehabilitation*

A striking example of the problems of rehabilitation is provided by the settlement of Ramanagar for the refugees of the Kali hydroelectric project (figure 1). The township of Supa, along with a number of minor villages will be submerged by this project and these several thousand families have to be provided alternative land in lieu of their paddy fields, coconut and arecanut gardens and other rich agricultural and horticultural land. Since practically all of such land is already under cultivation, they have been provided a hectare of non-irrigated hilly land for every hectare of submerged land, which is mostly irrigated lowland. Incidentally, it is to be noted that no attempt is being made to provide the refugees with alternative non-agricultural occupation based on the large amount of electrical power that will be generated by this giant hydel project.

This settlement is expected to be established at a place called Ramanagar near Londha on the border of Belgaum and North Kanara districts of Karnataka. This tract of land was earlier under reserved forest, and was taken over for resettlement around 1975. At the time of handing over, the entire tree crop was removed, and the land was allowed to lie fallow without the institution of any soil conservation measures at least till 1979. This land has attracted not a single peasant settler from amongst the refugees who are staying on their lands while the construction of the Supa dam goes on in 1979. In the meanwhile the topsoil on these unprotected hill slopes in this catchment area of one of the Kali project reservoirs has eroded over the last four monsoons making it by 1979 a desert unfit for cultivation for all times. The landscape stands desolate with a few empty school and temple buildings the only sign of the planned township. The Kali hydel project refugees are in the meanwhile agitating to refuse to go to Ramanagar and demanding another rich forested site called Barchi for their resettlement.

The clearance of the forest on the land earmarked for resettlement was clearly a grave error. The original forest was rich in tree species of the genus *Terminalia* which could have served as a base for a flourishing tasar silk industry. This could have been supplemented by bee-keeping and production of minor forest produce such as harada (*Terminalia chebula*) nuts. The remaining less valuable trees could have

been selectively cleared and cultivation of intervening patches of terraced and bunded land properly organised. This would have resulted in an economically more viable and ecologically sounder land use. Instead, the summary deforestation without the institution of any soil conservation measures has irreversibly ruined this large tract of land.

A second example of rehabilitation problems is provided by the Hidkal irrigation project on the Ghataprabha river in north Karnataka (figure 1). This reservoir nearing completion in 1979 is expected to eventually irrigate 2·63 lakh hectares in its command area, while it has submerged agricultural lands of only about 4000 hectares in extent. Nevertheless, the displaced population is not being rehabilitated in the irrigated command area, but rather in the catchment area, including places right on the fringes of the reservoir. The contribution of such settlements to increased siltation of the river is not documented, but appears to be significant.

3.2 *Labourers*

The execution of irrigation and hydroelectric projects involves the camping of several thousand labourers at the project sites. The labourers require timber for their huts and fuel for their day-to-day living, and so far they have always depended on the forest to meet these requirements. A notable example of the serious disturbance caused thereby to the forest is provided by the construction of Avalanche and other reservoirs on the Upper Nilgiri plateau (figure 1). These reservoirs are situated on a plateau at an altitude of around 2500 m, and are a cold, wet and windswept region for ten months of the year. Some 20,000 labourers were camped on this plateau for about 7 years for the construction of the reservoirs. There were no special provisions for housing them, and they had to live in ramshackle huts. This they could do only by keeping the huts continually heated by burning logs of wood. All this wood came from the famous evergreen shola forests of Nilgiris. These forests, rich in a number of endemic species are restricted to the higher hill tops of the Western Ghats and have largely disappeared due to plantation and other activities (Blasco 1971). Vast tracts of these virgin forests on the upper Nilgiri plateau have thus disappeared due to the activity of the labourers who had no recourse but to cut them down in order to survive (John Joseph 1978). This could have been alleviated, if not altogether avoided, if the labourers could have been provided with some tin or asbestos sheds and regulated fuel supply. This fuel supply could at least in part have been based on the wood cleared from the submersion area.

3.3 *Access to encroachers and poachers*

Hydroelectric and irrigation projects often open up previously inaccessible regions rich in timber and wild life to new agricultural settlers and poachers of both timber and wild life. It is feared that the colonisation of areas rendered accessible by the Silent Valley project is already underway, and will lead to irreversible damage (Nair 1979; Prasad *et al* 1979) (see figure 1). These settlers are likely to follow the pattern of settlers in the Idikki area who have largely colonised steep slopes unfit for cultivation on a sustained basis without very heavy investment in soil conservation measures.

Wealthier and better organised poachers take advantage of the improved access

facilities for smuggling out more valuable timber and poaching wild animals. These activities are naturally much more difficult to document. There is however considerable circumstantial evidence of this. For example, the once famous Dandeli wild life sanctuary was in 1977 on the verge of being dedeclared as a sanctuary because of the severe depletion of wild life consequent on the opening up of the area with the Kali hydroelectric project.

3.4 *Faulty planning*

Faulty planning of matters more directly concerned with the execution of the project as such has also led in a number of cases to an unnecessary loss of forest resources. Three examples, all from the state of Karnataka can be cited. The first example concerns the hydroelectric project on the Sharavathy river (figure 1). The large reservoir of Linganamakki feeding this project has filled to capacity only thrice since its commissioning some 20 years ago. This is because the estimated inflow into the reservoir from its catchment has not materialised. If the dam height had been restricted to a lower level such that the reservoir would be filled more regularly, not only would the cost of the project have been substantially reduced, but several thousand hectares of forest would also have been saved (Sharma 1978). As it is, the river Chakra is now being dammed, submerging further forest areas in Hosanagar Forest Range merely to feed further water to the Sharavathy hydel project. Moreover, the deforested upper submersion area of Linganamakki reservoir that rarely goes under water is under active cultivation most of the time, and must considerably add to the siltation of the reservoir.

The two other examples are from the Kali hydel project. A most elementary mistake has been committed at the Tattihalla dam site where some clearance area was incorrectly demarcated. As a consequence, considerable forest land (e.g. block 20, compartment 6 of the Sambrani Range) was unnecessarily deforested. Attempts are being made to put this back under teak plantation, but the *Eupatorium* weed, to which we will refer in § 4.3 below, makes such attempts difficult.

The last example is from Ambikanagar, the township created in place of the villages Amba-Jumba for the Kali hydel project. This area in the heart of the Dandeli wild life sanctuary was a forest famous for its herds of gaur. It was totally deforested at the time of its being handed over for the township. In the humid heat of the West coast, it is now a desolate and dusty place. It would have been a lovely hill resort, with its picturesque Syke's point if only such trees as were essential for roads and buildings were removed. As it is, all that Ambikanagar now has are a few small saplings planted by the roadside.

4. Consequences

The author believes that he has given enough indications, *albeit* qualitative, of the considerable magnitude of the loss of forest vegetation accompanying the irrigation and hydroelectric projects. This loss has a variety of consequences, all of which ought to be accounted for in the cost calculations of the project. These consequences may be considered under the following heads: (i) scarcity of forest produce, (ii) siltation of the reservoirs, (iii) ecological imbalances and (iv) decimation of biological diversity.

4.1 *Scarcity of forest produce*

The mounting scarcity of forest products in India has been well-documented as, for example, in the perspective plan for forests of Karnataka (Anon 1977b). The loss of forest land associated with projects has been a major factor aggravating this situation. Here, just one example may be cited from our own studies on the bamboo resources of Karnataka (Gadgil & Prasad 1978). Bamboo is the poor man's timber as well as the major raw material for the manufacture of paper in India. The yearly consumption of bamboo in Karnataka is around 160,000 tonnes while the yearly increment to the crop is only around 135,000 tonnes. This overexploitation has led to the wiping out of bamboo from many areas earlier rich in bamboo crop. As bamboo grows well along water courses, submersion under reservoirs hits bamboo particularly hard. Various projects in Kartnataka have therefore been a major factor contributing to the bamboo famine.

4.2 *Siltation of reservoirs*

The maintenance of a proper cover of vegetation in the catchment area of any reservoir is vital to its proper functioning. Such vegetation regulates the flow of water into the reservoir, preventing floods and maintaining water flow in the dry season, and more crucially prevents excessive erosion of soil (Dasmann *et al* 1973; Pareira 1973). That soil erosion in the catchment area and the consequent siltation of reservoirs has been a major problem in India is well-known (Anon 1978). Thus, for the 18 reservoirs all over India for which data are available, the observed siltation rate has exceeded the expected siltation rate in all but one of the cases. Moreover, the observed rate is generally 3 to 10 times as high as the expected siltation rate. The consequent drastic reduction in the useful life of the reservoirs has obviously serious economic implications, as for example, has been pointed out by Verghese (1977) for the greater Ganga river system. Although no data are immediately available for the Western Ghats reservoirs, it is evident that siltation must be a major problem.

4.3 *Ecological imbalances*

Apart from the more evident loss of forest wealth and siltation of the reservoirs, the large-scale deforestation for the projects can lead to subtler ecological imbalances. One such has been the enormous increase in the population of the weed *Eupatorium glandulosum* in the Kali hydel project area. This composite weed of the moister forests smothers out all tree growth in clear-felled forest areas and is totally unpalatable to all herbivorous animals. It renders forests more susceptible to fire and to losses of minerals through leaching. This weed of the moist forests of the Western Ghats has come to Kerala from Assam and has rapidly spread northward from there. When the Supa and other submersion areas of the Kali hydel project were deforested some five years ago, *Eupatorium* had just begun to establish itself in North Kanara. The vast stretches of clear-felled forest land provided the optimum habitat for *Eupatorium* which has now totally clothed these areas. It spreads far and wide through its wind-borne seeds. The vast population of *Eupatorium* in the deforested Kali submersion area is likely to be serving as a major infective centre for the further spread of this weed into Belgaum-Goa-Savantwadi-Kolhapur areas, and into the many new plantations being taken up in North Kanara itself.

4.4 *Decimation of biological diversity*

The tremendous genetic diversity of living organisms created by the hundreds of millions of years of evolution is a precious heritage of man. These have yielded to us a variety of foods, fibres and vital drugs and their maintenance is crucial to further progress in these fields. This is why the Food and Agricultural Organisation of the United Nations has launched a vigorous programme for the maintenance of genetic diversity of wild relatives of cultivated plants. The Western Ghats harbour a large variety of these, ranging from ragi, paddy, cardamom and pepper to mango and jackfruit. The critical importance of preserving all genetic diversity, not just that of presently utilised species, is also what has prompted the U.S. Supreme Court to hold up a dam that will destroy the only known population of a small fish—the snail darter.

The large impact of the irrigation and hydroelectric projects on the Western Ghats has sharply reduced the biological diversity of this region. These projects have selectively affected high rainfall areas, and areas near water-courses which tend to harbour evergreen tree species. They have thus contributed to the sharp reduction in the extent of evergreen forests on the Western Ghats (Pascal & Meher-Homji 1978). These forests have been a unique storehouse of many plant and animal species occurring nowhere else in the world, and it is only our profound ignorance which has masked the many extinctions of biological species—the many snail darters —that must have vanished. Father Saldanha (1979) points to just one example, *Hubbardia heptaneuron* Bor, a grass that was once known to grow in the spray zone of the famous Jog Falls of Sharavathy and nowhere else in the world. This species has apparently gone extinct with the execution of the Sharavathy power project.

Another threatened species of the Western Ghats is a monkey, the lion-tailed macaque (*Macaca silenus*). There are now only two surviving viable populations of this monkey left in the world. One of these is in the Silent Valley and the other in the Mundanthurai-Kalakad sanctuaries near the Agastyamalai peak (figure 1). This monkey depends for its survival on trees of genus *Cullenia*, and if the Silent Valley hydroelectric project materialises, most of this *Cullenia* forest will be submerged and the monkey wiped out. The Mundanthurai-Kalakad population is also threatened by other impending projects in that area. For all we know, with this monkey we may lose the only biological material that may enable us to combat some future epidemic of a new mutant of encephalitis.

5. Conclusions

5.1 *Sustainable development*

As we stressed at the beginning, economic development ultimately depends on the intensification of the use of the earth's natural resources. For a true development, however, this process should not lead to a rapid exhaustion of the resource being tapped, nor should it be accompanied by a needless destruction of another resource. This suggests that we should be particularly concerned about maintenance of the long life of the reservoirs, and avoiding the adverse consequences on other resources such as soil, forest and wild animals. Only by aiming at development that retains

its harmony with nature, by aiming at environmentally sound development, will we achieve true and sustainable development.

Our current development effort obviously fails in many ways when viewed from this perspective. Why is it then that these failures have attracted so little attention so far in our country? The author believes that this is so because the urbanised decision-makers are several stages removed from direct dependence on the natural resources, and are therefore immune from the immediate negative consequences of the unbalanced development process. It is the local peasants and tribals depending much more directly on the natural resources that bear the brunt of the immediate negative consequences of the development process (Bahuguna 1978; Kannan 1979; Mishra & Tripathi 1978).

This is well illustrated by the first case study. The destruction of the tree cover in the catchment immediately profited the urban society of Pune by providing cheap wood charcoal. The tremendously increased siltation rate would no doubt affect this city population in the coming years by reducing the life of the reservoir which supplies water to the city. These effects would however be felt only over several decades. The local peasants on the other hand have come to suffer much more rapidly, by the reduction in fertility of their hill slope land and the reduction in the availability of wild animal protein.

The author would therefore like to suggest that the interests of these weaker sections of our society provide a very good index of how harmonious with the environment, and thus how sound a development project is. If these interests are given serious consideration, we will orient ourselves towards planning of the overall land use for the long-term sustained utilisation of soil, water, vegetation and animal resources and it is only then that we will turn to planning for true, sustainable development.

5.2 *Perspectives for future work*

The concept of environmentally sound development throws up a whole series of scientific and technological challenges. Our whole scientific and technological establishment is geared today towards the solution of such problems as: how can we, over the next five years, extract the maximum amount of power out of the rivers of North Kanara? Even this problem is posed in isolation of another typical problem: how can we, over the next five years, produce the maximum amount of paper out of the forests of North Kanara? The point of view sketched above suggests that the scientific and technological establishment ought to address itself to a very different kind of problem, namely, how can the whole gamut of natural resources of North Kanara be developed so as to improve on a long-term basis the quality of life of the weaker sections of the society of North Kanara? We would then think not just of the power requirements of the Kudremukh Iron Ore complex, but also of the fuel-wood requirement of the people of North Kanara and of why all the avenue trees on the Sagar road are being chopped down. We would also think of bamboo requirements for rural housing in North Kanara, and not just turn to bagasse production for our paper factories once the bamboo stocks of North Kanara are finished. We will then plan the resettlement of refugees of the Supa dam as carefully as we plan the details of the powerhouses for the Kali hydroelectric project. It is an exciting scientific and technological challenge that deserves to be taken up.

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Plate 1

Figure 2. A view of the Panshet reservoir flanked by the now totally barren hill slopes.

Ecological and socio-economic consequences of water-control projects in the Kuttanad region of Kerala

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Abstract. An assessment of the external effects produced by water-control projects is essential, not only for the introduction of corrective measures, but also for revealing cases of "malignant development".

An attempt at the analysis of such externalities has been presented here through an examination of water-control projects in the densely populated, intensely cultivated, water-logged Kuttanad region of Kerala, and of the impact of such projects on the lives of different sections of the population in their "command areas".

The objective of these projects was to intensify paddy cultivation by (a) the speedy drainage of the floods (during the monsoon months) from the low-lying part of Kuttanad and (b) the prevention of saline water incursion during the summer months into the Vembanad lake. The actual project consisted mainly of a spillway at Thottapally to drain the flood waters and a regulator at Thanneermukkom to check the intrusion of saline water.

In fact, considerable divergence developed between the actual and intended effects of the project. The spillway succeeded in discharging only about one-third of the designed rate of flow of 64,000 ft^3/s, thereby proving to be far less effective in keeping down the flood level in Kuttanad than had been expected. The regulator produced, within four years of its commissioning in 1974, the following adverse effects, both on farming and on the general population of the region:

(i) a sharp decline in the catch of shrimps and fish which are brought into the Vembanad lake along with the incursion of saline water and which grow best in saline waters mixed seasonally with the fresh water in the lake;
(ii) a phenomenal growth in the aquatic weed, African Payal, with serious effects on the cultivation of paddy, and on transportation and fishing; and
(iii) the pollution of fresh water in the lake and other water courses in the Kuttanad area caused by the African Payal, and the interruption of the natural ebb and flow of tidal water into and from the water body, with deleterious effects on the health of the population in the region.

A brief description is also given of the negative impact of these effects on the lives of different sections of the population, particularly fishermen, paddy cultivators and lime-shell collectors.

Thus, the Kuttanad project demonstrates the vital need in such projects for going beyond mere engineering and economics and for maintaining a proper perspective of development in which the broader economic, social and environmental features are all considered.

Keywords. Water control projects; ecological consequences; external effects; saline water incursion; bunding; discharge of floodwaters; stagnation of water body; backwaters; growth of weeds; tidal ebb and flow; intensification of paddy cultivation; fishing: environmental factors; impact of projects.

1. Introduction

Agricultural development projects, be they for irrigation, flood control, soil conservation, bunding or control of salinity, not merely help increase agricultural production, but also interfere with the environment. Such interference is bound to have

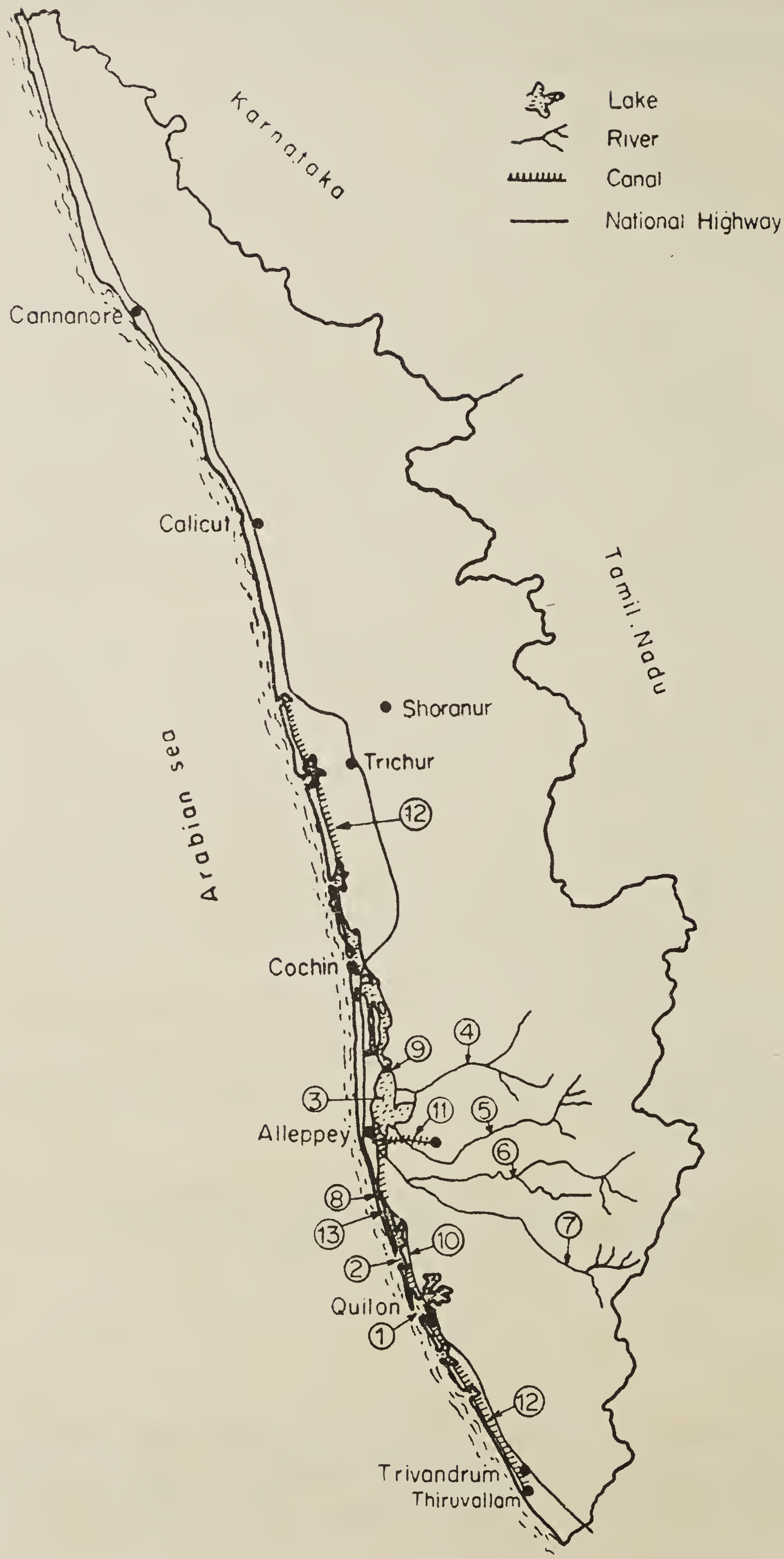

Figure 1. Map of Kerala showing the lakes, rivers, canals, etc. 1. Ashtamudi lake. 2. Kayamkulam lake. 3. Vembanad lake. 4. Meenachil river. 5. Manimala river. 6. Pamba river. 7. Achenkoil river. 8. Spillway at Thottapally. 9. Regulator at Thanneermukkom. 10. Quilon-Alleppey road (National Highway). 11. Alleppey-Changanacherry road. 12. Trivandrum-Shoranur canal. 13. Thrikunnathupuzha.

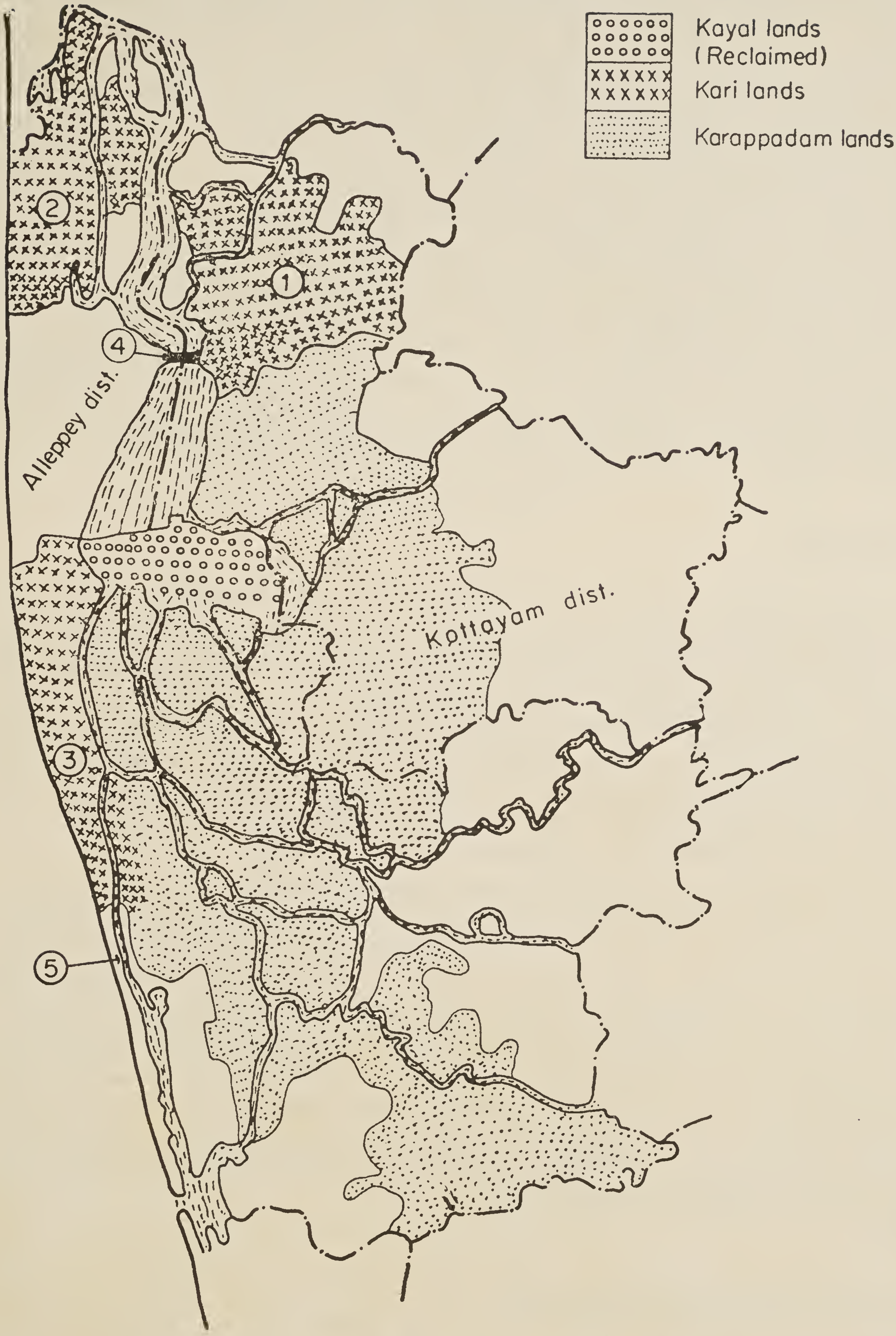

Figure 2. Map of Kuttanad region showing different types of lands, the regulator and the location of Thrikunnathupuzha referred to in the text. 1. Vaikkom-Vadayar area. 2. Thuravoor area. 3. Puracad area. 4. Regulator at Thanneermukkom. 5. Location of Thrikunnathupuzha.

both short-run and long-run external effects, direct or indirect, on the lives of the people in their 'command areas'. And such externalities need not, always or uniformly, be beneficial. While project evaluation techniques are supposed to consider externalities, the latter have very rarely been incorporated in actual studies. The usual argument for this omission is that most of the external effects are not amenable to quantification, and, wherever amenable, they seldom permit satisfactory valuation. Problems of quantification and valuation do exist, but it is not difficult to assess the nature and extent of the external effects in general terms, and to identify the sections of the population affected by these effects. Such assessments are essential for the introduction of corrective measures; but, more importantly and in a fundamental sense, they bring to light specific cases of 'malignant development'.

This paper is an attempt to examine and analyse the nature of externalities, most of which are diseconomies, of various water-control projects implemented in a densely inhabited and intensely exploited water-logged region in Kerala, and their impact on the lives of different sections of the population in that region.

2. Kuttanad

Kuttanad (figures 1 and 2), a low lying area extending over 874 km², had in 1971 a population of 1·46 million people distributed over 79 villages in the Kottayam and the Alleppey districts. Of the total area, approximately 304 km², are garden lands with an average elevation of 1 m *above* sea level, and are presently used for paddy crops. The area *below* sea level is subjected annually to severe flooding during both the monsoon periods by water drained by four rivers (Meenachil, Pamba, Manimala and Achenkoil), with a discharge of 1,89,000 ft³/s during the south-west monsoon period alone. About 80 km² comprises the Vembanad lake and the various water courses including rivers and man-made canals.

Kuttanad is a densely populated area with 1,128 persons per km² against the average of 549 for Kerala and 182 for India in 1971. However, the area available for human settlement being very small—the garden lands only accounting for about 35% of the total area—the effective density of population is much higher. The high density of population in the area even as early as the beginning of the century, and the moderate to high rates of growth during the ensuing period, the conditions of near-stagnation in the non-agricultural sector, and the absence of any basic institutional changes for ameliorating the economic backwardness of the poor, remain the major features of the economy of this region. This is the background against which we examine the impact of the major water-control projects implemented in Kuttanad for purposes of agricultural development.

3. Water-control projects in Kuttanad

Efforts to develop Kuttanad as a rice-growing area began more than a century ago. Since the flood waters carry a large volume of fertile silt, it was recognised quite early that much of the low-lying land could be used to grow a rich rice crop if the flood waters were effectively regulated. In the early phases, land reclamation and flood-control work were largely undertaken at the initiative of private farmers,

with the active assistance of the State (Pillai & Panikkar 1965). Though the area so reclaimed steadily increased, almost all of it was used to grow only one crop of paddy a year.

In the 1930s, faced with severe shortages of rice, the then Government of Travancore explored the possibilities of raising two crops of paddy in the reclaimed lands. The resulting studies identified two preconditions for intensifying paddy cultivation in the region: (i) the speedy drainage of the flood during the north-east monsoon season, and (ii) the prevention of saline water incursion during the summer months into the Vembanad lake. The project however was given concrete shape only some two decades later and consisted of (i) a spillway at Thottappally meant to drain off flood waters, (ii) a regulator at Thanneermukkom meant to check the intrusion of saline water, and (iii) a 42 km long link road between Alleppey and Changanacherry (figure 1). The spillway was commissioned in 1955, but the regulator and the link road have had a rather chequered history. The construction of the regulator, which was started in 1958, was still incomplete when it was commissioned by the end of 1974. The Alleppey-Changanacherry road also remains incomplete mainly due to the non-completion of 3 connecting bridges.

3.1. *Spillway at Thottapally*

The search for a permanent solution to the problem of floods in Kuttanad started as early as 1934 by the then Government of Travancore. In 1937, two Italian engineers commissioned by the Government suggested the cutting open of a floodway channel from the Vembanad lake, at Aryad just north of Alleppey, to the sea. Two years later, another suggestion to cut open a spillway channel into the sea at Thottappally about 20 km south of Alleppey was made by an executive engineer of the Government. The latter suggestion, though accepted by the Government, was not taken up till 1951.

When work on the construction of the spillway, with a length of 368 m was started in 1951, the estimated cost of construction was Rs 5.7 millions. The spillway was commissioned in 1955.

The spillway is reported to have been designed after detailed hydrographic and hydrological studies to determine the extent of maximum floods, the outflow through the existing water-ways, and the anticipated requirements of the spillway channel to be constructed. The maximum discharge of water from the three rivers Manimala, Pamba and Achencoil, all of which empty into the lower reaches of Vembanad, was estimated to be about 189,000 ft^3/s during the peak monsoon months of July and August. Of these, 5,000 ft^3/s of water would escape into the Kayamkulam lake through the openings along the Quilon-Alleppey road which is on a general level with the garden lands in Kuttanad area. The spillway at Thottapally was designed to discharge 64,000 ft^3/s of water which, if realised, would have meant a speedier subsidence in the flood levels within Kuttanad and, consequently facilitated early cultivation.

When the spillway was commissioned in 1955, it was noticed that it could not discharge more than one-third (i.e., 20,000 ft^3/s) of the designed capacity. As a result, the construction of the spillway has not made any perceptible improvement in the control of floods in Kuttanad.

A number of factors seem to have contributed to the failure of the spillway to reach the original target of flood discharge. One of these factors is the rise in the sea level during the monsoon and the consequent formation of a sand bar on the seaward side of the spillway. It appears that this 'piling up of water' was not taken into account in designing the spillway. The present position is that, before the monsoon attains full fury, the sand bar has to be cut open for a sufficiently wide length before the spillway is opened to let the flood waters drain into the sea; otherwise the sea water will find its way into the channel through the spillway and reverse the flow of flood waters.

Another factor concerns the location of the spillway. Doubts as to whether the present location is the right one arise from the actual variations in the water level, as well as the direction of the flow of water, within Kuttanad region during the different months of the years and especially during the monsoon.

A much more serious factor seems to have been the deviations from the original specifications in the construction of the 1,311 m-long and 368 m-wide approach channel to the spillway. The present width of the channel is considerably smaller than the original design specification due mainly to difficulties in the acquisition of land for the purpose.

It has now become very difficult to initiate corrective measures to increase the rate of discharge of water. Not only are substantial additional investments needed, but the Cochin Port authorities also fear that, if more flood waters were to be let out through the spillway, the problem of siltation in the channels of the Cochin Port will be greatly aggravated.

3.2 *Regulator at Thanneermukkom*

The problem of salt water incursion from the sea into Kuttanad during summer was sought to be solved by constructing a salt-water barrier, 1,402 m-long and located at Thanneermukkom, about 22·5 km north of Alleppey. The regulator has been constructed across the lake at the point where the width of the lake narrows down to the minimum. The construction of this regulator took an inordinately long time. The work was started in 1955 and by 1973 only two-thirds of the construction was complete. The remaining one-third was temporarily bunded with sand, clay, etc. by mobilising local labour. Though incomplete, the regulator was commissioned by the end of 1974. Towards the end of December each year when the saline water incursion into Vembanad lake begins, the shutters in the regulator are lowered and are kept closed till the end of May when the pre-monsoon showers reverse the flow.

The combined effect of the spillway and the regulator was expected to increase the area under double-crop paddy by enabling (i) the date of sowing of the first crop to be advanced in areas subject to the north-east monsoon floods, and (ii) the raising of a second (summer) crop by preventing the incursion of saline water in the summer months and using the fresh water in the Kuttanad water body for irrigation. In fact, the cultivation was found to require raising and strengthening of bunds so as to withstand the north-east monsoon floods. Whether this was due to the failure of the spillway to reach its designed discharge capacity, or whether it would have been found necessary even if the spillway were successful, is not clear. In any event, the need for this bunding does not appear to have been anticipated in the original

project concept, and it was only in 1971 that a separate project for this purpose was prepared by the Government of Kerala and entrusted to the Kerala Land Development Corporation, specially created for this purpose.

3.2a. *Impact of the regulator.* Implicit in the design and location of the regulator seems to have been an assumption that variations in the intensity of salinity between different parts of the region are not significant. In fact, the Kuttanad area is marked by wide variations, not only in soil and topographic conditions and the incidence of flooding, but also in the intensity of salinity during summer months. The area can be divided into eight sub-divisions based on the above criteria; these can be further grouped into three broad categories representing distinct soil-topography-water conditions. They are (i) the Kayal lands, (ii) the Kari lands, and (iii) the Karappadam lands (figure 2).

(i) *The Kayal lands.* These lands, covering approximately 8,100 hectares, were reclaimed in the southern-most part of the Vembanad lake. The salinity problem affects this part of Kuttanad towards February by which time the traditional single crop paddy would have been harvested. Prevention of saline water incursion clearly should help this area to raise a second crop during summer.

(ii) *The Kari lands.* These are swampy areas, totalling about 6,100 hectares, with black peaty soil (with a high proportion of carbonatious wood) and high acidity. There are two Kari land areas: one in the northern (Thuravoor and Vaikom-Vadayar) and the other in the southern (Puracad) extremities of Kuttanad (see table 1). The Kari lands are not only of poor quality but are beyond the range of influence of the regulator. Prevention of saline water incursion clearly should help this area to raise a second crop during summer.

Since the Vaikom-Vadayar and Thuravoor areas lie north of the Thanneermukkom regulator, the regulator does not prevent the incursion of saline water into them. In these areas, temporary tidal bunds have to be put up, as in the past, across the water courses from the Vembanad lake during the dry season every year. On the other hand, saline water from the Vembanad lake does not reach Puracad area at all. Salinity incursion takes place here through the Ashtamudi lake (to the south) which is checked by a lock at Thrikkunnathupuzha across the Trivandrum-Shoranur canal, about 10 km from Kayamkulam. As mentioned earlier, the soil is of inferior quality and acidic and hence raising a second crop was reported to be not remunerative at the current (1977–78) level of price for paddy.

(iii) *The Karappadam lands* These comparatively shallow lands coming under 'old reclamations' and covering a much larger area (42,500 hectares) are also widely distributed among different parts of Kuttanad (see table 2). The upper portion of the area lies 0·3 to 1·0 m, and the lower portion 1·0 to 2·3 m, *below* mean sea level.

Table 1. Distribution of Kari lands

The Kari lands	Hectares (approx.)
1. (a) Vaikom-Vadayar area	2,025
(b) Thuravoor area	2,025
2. Puracad area	2,025

Table 2. Distribution of Karappadam lands

The Karappadam lands	Hectares (approx.)
North Kuttanad	10,120
Central Kuttanad	10,120
Kuttanad Proper	10,120
Upper Kuttanad	12,145

North Kuttanad, being an area adjacent to Thannermukkom, used to be affected by the incursion of saline water during summer. Such incursion had been checked even before the regulator was commissioned, by putting up temporary tidal bunds across canals and rivers. These bunds used to be opened up as soon as the harvesting was over, without waiting for the onset of the monsoon. The advantage of this method is that the salinity problem was effectively checked during the critical period of paddy cultivation without adversely affecting the other occupations (notably fishing). The commissioning of the regulator has obviated the need for annual bunding during the dry season, but as we shall see later, it has created other problems.

In the remaining areas of Upper and Central Kuttanad, salinity was never the primary impediment to double-cropping because it reached these areas only in April by which time harvesting of summer paddy would have already been completed. Even in those parts of the area experiencing salinity, the saline content was so small that it was not a major constraint. The more important problem of this area, if at all, is one of controlling floods.

It would therefore seem that the benefit from the regulator in facilitating a second crop of paddy has been confined mainly to the 8,100 hectares of Kayal lands and 10,120 hectares of North Kuttanad, even though little is known about the extent to which this has been realised in fact. The remaining areas were either not affected at all by the regulator; or the effect was not felt significantly because the problem of saline water incursion was not a critical constraint to paddy cultivation in the areas. This view is supported by the fact that a significant portion of the Kuttanad area had switched over to double-cropping even by 1968-69 when the regulator was not ready for operation. By strengthening the existing bunds, the farmers used to raise a second crop in spite of severe problems involved in the cultivation of the second crop. Whenever the prices of paddy were high, double-cropping was profitable.

Detailed data required to verify the above impressions could not, however, be obtained. We understand that, until 1975, when the paddy prices were sufficiently high and rising, the area under second crop in Kuttanad was steadily increasing, and even spreading to the inferior Kari lands. Since then, the increased cost of cultivation (arising from, among other things, the high incidence of pests, and the spread of African Payal*) combined with a decline in paddy prices, is reported to have considerably reduced the profitability of, and led to the decline in the area under the second crop, particularly in the marginal (Kari) lands.

*The botanical name of this weed is *Salvinia Auriculata*. This non-flowering plant belongs to the family of water feros. It is believed to have come from Africa because this is widely found in the water-ways of Zambia, Kenya and Rhodesia. Unlike the water hyacinth, African Payal is a small plant with leaves spread on the surface; the plant grows at a rapid rate and becomes denser and thicker.

While the increase in the incidence of pests and the fall in paddy price are due to factors other than the commissioning of the regulator, the latter was directly responsible for the extraordinarily rapid spread of the African Payal. The absence since 1974 of saline water incursion during summer has provided excellent conditions favourable for the growth of the African Payal since saline water destroys it and prevents its reappearance to a considerable extent. Apart from the problems it has created in the cultivation of paddy, the regulator has also led, during the early sixties, to the spread of African Payal, which has become a serious problem.

Several ways of removing the weed have been under consideration. Chemical destruction, though possible, might lead to adverse effects on aquatic life, plant crops and water and hence it is not recommended. Biological destruction by introducing certain parasites was also thought of; but its repercussions are not known. The current practice is to physically remove the African Payal from the paddy fields, but not from water courses or lakes. In fact, in certain areas, the weeds are pushed into the water courses from the paddy fields. Thus, the only feasible solution seems at present to be to physically remove them by mobilising labour. This would certainly involve financial cost and ways of mobilising and sharing the cost will have to be found.

In places where the growth of the weed is highly dense, transport by country boats has become practically impossible. Boats are pulled out from the weed traps with the help of motor boats. In such areas, country boatmen and fishermen are the worst-hit in the circumstances. The formation by the weed of a thick velvet-like sheet on the entire water surface prevents sunlight from reaching the bottom of the water body and adversely affects the utilisation of the nutrients for the growth of aquatic life. The growth of African Payal, coupled with the stagnation of the water body, has provided an environment highly suitable for the breeding of mosquitoes on a much larger scale than before.

The utilisation of the weed as raw material for industrial purposes or as organic fertiliser has not yet been realised. There are several problems: the moisture content of the weed is over 90%, the cellulose content only 2%, and the NPK content, less than 2%.

Thus, the spread of African Payal has affected almost every aspect of life of all the sections of people in Kuttanad; in particular, it has generated a number of problems such as the obstruction of transportation and fishing, the pollution of the water-bodies and the intensification of mosquito-breeding.

3.3. *Alleppey-Changanacherry road*

The third associated project sponsored by the Government is the construction of the Alleppey-Changanacherry road. Kuttanad is criss-crossed with innumerable natural and artificial water-ways giving access to every part of the region through country boats and motorised boats, both big and small. Apart from the advantage of accessibility, the water transport system is also cheap. However, the system has the disadvantage of lack of speed. Road transport was thought to be quicker, and hence more efficient. Therefore, a project for the construction of a 42 km-long road running East-West and linking two major towns, Alleppey and Changanacherry, was started in the early fifties. The project still remains incomplete on account of certain difficulties particularly the high cost of building bridges at three

places. For the present, ferry services are provided in these three places. This 12m-wide road constructed above the flood level acts as a barrier to the free movement of flood waters from the Upper Kuttanad, the area worst affected by floods. The construction of this road seems to have aggravated the flood problems in the part of the region lying south of the road.

4. Impact of the projects on fishing

Kuttanad has a water body with an abundance of nutrients; it receives strong sunlight which reaches a few metres below the water surface and has a temperature conducive to plentiful production of water-borne fauna. However, no detailed account is available of the fauna of this region except of the fish species (Samuel 1977). It is likely that the lake bed may have a variety of very rich fauna. According to a study conducted in 1948 (Samuel 1977), the water body in Kuttanad has 32 fish species and to this should now be added *Tilapia mossambica*, an introduced species which has established itself in this natural habitat. Some of the species identified earlier have by now become scarce or completely extinct in this area owing to the lowering of salinity and the thick growth of African Payal.

The populations of the giant fresh-water prawn and the frog have also declined during the last decade owing to excessive and indiscriminate exploitation. The giant prawn breeds in the brackish waters; changes in the salinity conditions of the breeding grounds are likely to adversely affect its life cycle.

In the past, frogs constituted a very abundant resource of Kuttanad. Since frog legs have a very attractive export market, frog-catching during the monsoon has become a highly profitable business in this area; this activity leads to the rapid depletion of frogs. An increase in the frog population is considered by the farmers to be an effective check on the multiplication of the brown hopper, a species of pest which does serious damage to the paddy crop. In fact, some persons even hold the view that there exists an inverse relation between the brown hopper and the frog population.

The estuaries and the backwater systems of the Kerala coast are the nurseries of several species of marine shrimps. During the early stages of their life, prawns enter the backwaters and grow in them for about six months by feeding on the detritus. Shrimps are caught when they return to the sea. The construction of the regulator has severely reduced the backwater area available for the prawns to spend their larval and growing stages of life.

Only very few among the 33 species of fish identified in this area have commercial value. Those species of fish which show a marked preference for a brackish water environment (such as *Ambasis dayi, Cerres sp.*) have suffered a total or partial extermination owing to changes in the water conditions. With the change in the environment, including the prevention of the inflow of saline water into the backwaters, the important species of shrimps and other fishes have been exterminated and the growth and distribution of.some other species generally restricted.

Estimates of the quantity of fish obtained from the Vembanad lake are not available for recent years. The Vembanad lake is the largest of the Kerala backwaters with a length of 96·5 km extending over an area of 256 km^2. It has a depth of 2 to 5 m and the tidal influence is comparatively small. According to one estimate,

the fish landings from Vembanad lake were 1,252 tons in 1965, of which the Chinese net contributed 518 tons, stake net 695 tons and boat seine 38 tons. The composition of fish caught from the backwaters has been found to be as follows:

Prawns	..	60–70%
Mullets	..	11%
Pearl spot	..	10%
Cat fish	..	9%
Others	..	1%.

For the entire Kerala backwaters the composition of the local catch in 1970 was 14,000 to 17,000 tons of fish, 88,000 tons of clams and 1,70,000 tons of molluscan shells.

The fishing community is perhaps the major group whose interests and livelihood seldom received any attention in all the developmental work carried out in Kuttanad. There are 46 fishing villages but no reliable estimates are available on the number of persons engaged in fishing; it is believed, however, that their number may come to 20,000. It is reasonable to estimate that during the summer months, the average daily catch of shrimp from the Kuttanad area was 5 tons, which is valued at Rs 50,000. The shrimp fishery has failed completely since the commissioning of the regulator. Along with fishing, the economic condition of the fishing community has also suffered.

The prevention of the flow of sea water into the lake during summer has led to the decline or disappearance of several fish species that grow in saline water. Various studies conducted have suggested that the growth of fish population in the backwaters depends very much on a number of environmental factors such as temperature, salinity, dissolved oxygen, alkalinity, etc., which are greatly influenced by the tidal rhythm. Absence of the flow of water in and out of the backwaters, leads to changes in the environmental factors which affect adversely the production of plankton and organic matter which form the food of various species of fish (Jhingran 1975). Decline in the catch of fish has resulted in lack of employment for the fishermen and their consequent impoverishment, particularly because no alternative employment opportunities exist for them. Further, during the period when the regulator is not closed, the growth of African Payal causes considerable difficulty for fishing: the nets get damaged and transportation in country boats becomes difficult and often dangerous. The regulator has also caused a decline in the shrimp fisheries even in areas outside the direct influence of the regulator. The failure in this region is due to stagnant water which prevents the operation of the stake nets.

5. Impact on other occupations

Apart from cultivation of paddy and fishing, there are other important occupations in Kuttanad: (i) lime-shell collection from the Vembanad lake, and (ii) retting and defibering of coconut husks to cater to the raw material requirement of the coir industry. The last two occupations are based on the cultivation of coconut.

(i) *Lime-shell collection* The fishing resources of the Vembanad lake in Kuttanad also include what are called molluscs (lime-shells). The living and the dead remains of species known as *Ostrea*, *Velorita*, and *Meretrix* supp. are the most abundant in

the Kuttanad area. The sub-soil deposits are in layers of 30 cm to 50 cm thickness. All these species of molluscs have optimum ranges of salinity for their breeding and the changing conditions of salinity are likely to adversely affect their life cycles.

Usually, lime-shells are collected from September to May, i.e., throughout the year except during the south-west monsoon season. The annual output, estimated in 1970, is reckoned to be 1,70,000 tons.

The mollusc shells, which provide lime, breed in saline water and the annual incursion of saline water provides the environment suitable for the reproduction of these molluscs. Stagnation of water due to closure of the regulator and the consequent decline in salinity, prevent the settling and growth of these shells. Though lime-shell collection is largely carried out manually by persons going out into the lake in country boats, large-scale lime-shell collection by dredging is also resorted to by the two state-owned companies, Travancore Cements and Travancore Electro-chemical Industries. Such dredging operations prevent the growth of mollusc shells because the sludge released while washing the shells is deposited back in the same area. This method of lime-shell collection is a concrete case of a renewable resource becoming a non-renewable one through environmental degradation. The feasibility of using the dredge sludge for land reclamation merits consideration.

The closure of the regulator during the summer months, when the incursion of saline water takes place, will have an effect on the long-term availability of lime shells. The present deposits may be available for collection for a few more years, but in the long run, the regeneration of the shells will be prevented by the closure of the regulator.

(ii) *Retting and defibering of coconut husks*. Coir-processing, which is confined to a few villages in Kuttanad, is mainly an agro-based occupation, and about 95% of those engaged in defibering and spinning are women. In considering the impact of the regulator on coir-processing, it must be noted that, while retting of raw-husks takes three months in saline water, it takes 10–12 months in fresh water. Hence, retting has been seriously hampered by the operation of the regulator.

6. Other impacts

Besides the effects on cultivation of paddy, fishing, lime-shell collection and retting of coir described above, a few other problems have also cropped up since the commissioning of the regulator.

The closure of the regulator stops completely the tidal ebb and flow and results in the stagnation of the entire water body outside the regulator. Since there is no rain during the period when the regulator remains closed, the water level in the canals and other water courses goes down and, within a matter of a few weeks, the water gets polluted. Except for a few affluent households, the canals and the other water courses are the only source of water for the entire population for drinking, bathing, washing, retting of coconut husks, and even for discharging human wastes. In the past, the daily tidal ebb and flow produced a sufficient flow of water to ensure natural drainage and prevent the pollution of the water body. Now, the water body gets polluted quickly, resulting in the spread of diseases like dermatitis, jaundice, colitis and amoebic dysentery. The extent of the incidence of these diseases has not yet been quantified.

During the five months when the regulator remains closed, the water level north of the regulator rises by 60 to 90 cm with a corresponding decline in the southern parts of Kuttanad, i.e., where salt water intrusion is prevented. Therefore, even in garden lands in the north of the regulator, water seeps in and remains stagnant causing considerable damage to the healthy growth of coconut and other trees. The area also becomes an excellent breeding centre for mosquitoes. Since water remains stagnant with a thick layer of African Payal, the southern side also provides ideal conditions for the breeding of mosquitoes.

Though salt water incursion was a constraint in the past for the cultivation of the paddy crop, saline water used to be let into the fields immediately after harvesting. This saline water used to prevent the growth of weeds and pests and led to very high paddy yields because of the absence of weeds, which is a major problem in most other paddy lands in the State. At present, the absence of salinity in the water has provided conditions favourable to the growth of weeds—thus, paddy yields have declined.

The entire Kuttanad area comprises marsh lands, and the decayed vegetable matter below 2·5 to 5 cm of the top soil has a high percentage of carbonatious wood. The resulting acidity of the soil has been a major constraint in the cultivation of paddy. The traditional solution to this problem consisted of leaching the soil—this was done by applying lime immediately after harvesting and by letting in water for the remaining period. The tidal ebb and flow helped dissolution of the acidic material and its removal from the land. Today, this natural washing of land does not take place when the regulator remains closed. Since the top soil retains its acidic nature, paddy cultivation has been adversely affected.

Finally, with the closure of the regulator during summer, the water level in the lake goes down significantly, partly due to evaporation losses and partly due to pumping of water to those lands where a summer crop is raised after harvesting and/or a second crop is grown. This has led to a water shortage in the dry lands and diminished the productivity of coconut trees.

7. Implementation of a recent Land Development Project

One of the major problems faced by the cultivators in raising a second crop of paddy was the flooding of the fields due to breaches in the existing temporary bunds during the north-east monsoon. Since increasing the production of paddy was accorded high priority by the State Government, a scheme was drawn up in 1974 for the construction of permanent, but submersible, bunds, 1,966 km long, to protect paddy fields of an area of 52,000 hectares (1,25,000 acres). The scheme was submitted to the Agricultural Refinance and Development Corporation for refinancing a major part of the total outlay of Rs 200 million. Some additional infrastructural facilities were also felt necessary for which an amount of Rs 43 million was earmarked. For the implementation of the project a new corporation known as The Kerala Land Development Corporation Limited (KLDC) was formed.

The farmers have to repay the cost of construction of bunds at 9% interest rate in 15 years with a moratorium for the first three years. The cost per acre will vary from place to place depending on the area covered and the technical specifications for protection. The estimated range of cost is given in table 3.

Table 3. Estimated range of cost for bund construction and allied works.

Range	No. of blocks	Area in acres
Upto Rs 1,000	133	54,082
Between Rs 1,000 and Rs 1,500	129	39,716
Between Rs 1,500 and Rs 2,000	79	16,427
Above Rs 2,000	97	13,943

Source: Kuttanad Development Project, Government of Kerala, Trivandrum, 1974.

The debt services charges according to the original estimates may not exceed Rs 236 per acre per annum for the maximum loan amount of Rs 2,000 per acre.

This particular project was subjected to a detailed social cost-benefit analysis (Kannan 1975). The project was found to be socially feasible in view of the high proportion of labour involved both in the construction of bunds and in obtaining the materials for such construction. However, the net social benefit of the project depended on two crucial assumptions: (i) the completion of the project within the stipulated period of six years and, (ii) the level of yield of paddy at 30 quintals per hectare. (It was shown that, if the yield of paddy were to decline to, say, 24 quintals per hectare, or there was a decline in prices, the farmers would find the project uneconomical.) Both these assumptions were later proved incorrect. The progess in implementation was extremely slow and a number of factors contributed to the decline in the returns for the second crop.

Though the idea of permanent bunding of paddy fields was welcomed, the implementation of the scheme has run into rough weather. A number of reasons can be cited for the very disappointing performance of this scheme. First of all, the fertility of the land in Kuttanad varies with soil type and other factors like extent of acidity in the soil. Naturally the value, as well as the productivity of land, varies from region to region. In areas such as the Kari lands, where the value of land is only about Rs 2,500 per acre, farmers are reluctant to undertake an investment of up to Rs 2,000 per acre with a repayment obligation of Rs 230 per acre for 15 years.

The intuitive economics of the farmers would suggest to them that it is better to incur an annual expenditure of Rs 100–120 per acre on repairs to bunds, rather than repaying double that amount annually for 15 years. The question therefore arises whether the improvement/construction of the bund envisaged is the least-cost one. Farmers believe that it is a high-cost work and, given the uncertainties of the second crop, they are hardly enthusiastic about the project. It should be borne in mind that public work programmes, whatever their type, are rarely oriented to finding out ways and means of cost reduction; often they tend to be costlier than they ought to be. In fact, only 133 out of 438 padasekharams have joined the scheme so far. By January 1978, the total length of bunds already constructed was just 134 km, i.e., hardly 7% of the total length to be covered under the project. The area benefitted was about 6,600 acres. The project was launched in 1974 and the authorities claimed that it woud be completed in about six years, i.e., by the year 1980. As things now stand, it would indeed be surprising if the KLDC completes at least one-fourth of the work by that year. It was reported that work was in progress in another 338 km covering an area of about 24,000 acres.

The raising of a second crop in the paddy fields has not been hampered by the

absence of permanent bunds. In fact, double-cropping of a large part of the area was started as early as 1968. When the Kerala Land Development Corporation scheme was on its way to implementation, CARE, a voluntry international organisation, also came up with a programme for financing (in the form of providing wheat) the bunding of fields. Such bunding did not, however, envisage rubble pitching but only widening and strengthening of bunds by dumping clay, sand, etc. The sides of the bund facing the lake/water courses could be protected by planting grass and screw pine. Since this programme was much cheaper and did not involve any financial commitment to the cultivators, they adopted this scheme and naturally did not want to accept the KLDC scheme with financial commitment for the next 15 years. The extension of the CARE programme was prevented by the government by making it obligatory on the part of the cultivators to get the approval of the KLDC for any developmental work.

Doubts were also raised by some persons about the technical aspects of the bund construction. A number of breaches have developed in many parts of the newly constructed bunds; this has only helped to further erode the credibility of the project. Further, the unduly long time taken for the construction of the bunds and the misgivings about the 'contract' system adopted for execution of the work have reduced the confidence of the cultivators in the whole scheme. In theory the construction work is entrusted to a cultivator who is a nominee of the beneficiaries in a given area. However, in practice, such cultivators are also contractors and their style of functioning hardly differs from that of the conventional contractors.

8. Concluding observations

The preceding discussion has shown how the water-control projects in Kuttanad have produced results contrary to their goals and have even endangered the natural environment. These projects have affected all the subsystems of the environment, *viz.* physical, biological and human (Biswas 1978). Through changes in the quantity of water (i.e., the level and discharge of water during summer) and in its quality (i.e., the concentrations of nutrients and the level of salinity), the physical subsystem has been affected, adversely and perceptibly. This has, in turn, interfered with the biological subsystem—the availability and composition of the fish population has been adversely affected and there has been a rapid spread of aquatic weeds like the African Payal. These changes in the physical and biological subsystems have had their impact on the human subsystem as well; the fishermen in the region have been the worst-hit; but other sections too have suffered. The general population, particularly the poorer sections, is now experiencing problems of transportation and public health.

A number of factors, both technical and institutional, have contributed to such a state of affairs. The location and design of the spillway did not take sufficient cognisance of the oceanographic and hydrological features of the area. The design and operation of the regulator did not anticipate the occurrence of saline water incursion at different places in the Vembanad lake at different points of time and the consequent spread of water in the surrounding paddy fields. It appears that non-technical parameters were ignored in the design and execution of projects.

Since the approach channel could not be constructed according to the required

specifications because of land acquisition problems, the project authorities had to reduce the channel to a size much smaller than warranted by technological requirements. This constitutes one of the main reasons for the discharge of flood waters through the spillway being on a much lower scale than required. The neglect of non-technical parameters and the reduction of the size of the projects leads directly to the question of institutional constraints on developmental efforts.

So long as intensification of paddy cultivation remained remunerative, little concern was shown for the economic and ecological consequences of the operation of the regulator on the fishermen (constituting about 20,000 families), coir workers and other small communities of workers. Once the additional crop ceased to be profitable, and the ecological effects of the regulator mounted, concern rapidly developed for the harmful consequences of the regulator.

The construction of permanent outer bunds for the paddy fields had been a long-felt need. However, the project was started at a time when paddy prices had started falling. Further, technical drawbacks in design and construction of the high-cost nature of the project were quickly detected by the farmers and the project turned unpopular among them.

Initially, the agricultural labourers, who constitute 11·2% of the population, expected that the projects would lead to intensification of paddy cultivation, and therefore to increased employment and earnings. Only when the negative ecological impacts of the projects became apparent and began ruining the additional paddy crop did the agricultural labourers of the region react to the harmful consequences of these projects.

The lives of the people had begun to suffer long before the paddy crop was first affected. But, no attempt has been made, even after the experience of these adverse effects, to examine them beyond the routine scrutiny of engineering details. A proper perspective of development in which the broader economic, social and environmental factors play a crucial part is essential. The need to go beyond engineering and narrow economics is self-evident. It is not enough to bring out the costs and returns, either private or social. That private profitability calculation is not the relevant criterion in the evaluation of public projects, is accepted in principle by many, but seldom recognised in practice. Even social benefit-cost calculations, which help to provide a broader framework for project analysis, do not go beyond attempts at systematic incorporation into the analysis of both direct and indirect effects. On the one side, social benefit-cost analyses are beset with a number of quantification and valuation problems; on the other, they are inadequate for understanding the impact of the projects in terms of their interaction with other projects and social and economic processes at work in a given region. Public project analysis being a crucial problem in the planning process, only an interdisciplinary approach in which the technological, economic, social and environmental factors are analysed within a common perspective of development, might help to provide a realistic picture of what is likely to happen. It is evident that the acceptability of a project would revolve round issues such as the sections of the population benefitted, the sections which bear the brunt of the social costs and the different impact of the projects on the overall levels of living of the different sections of the population. These are primarily political issues the meaningful resolution of which, in the framework of a democratic pluralistic society, would require the active participation of the people. Academicians and technicians would be rendering an invaluable service to

the people if they could make honest attempts to articulate properly the variety of issues involved and offer meaningful alternatives.

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Storage of solar energy

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Abstract. A framework is presented for identifying appropriate systems for storage of electrical, mechanical, chemical, and thermal energy in solar energy supply systems. Classification categories include the nature of the supply system's setting; the type of energy supplied; the type of solar energy collection system used (including 'indirect' solar energy, such as wind and hydropower); the type of energy stored; and some other characteristics of the storage system. A global insolation summary is used to exhibit the diversity of requirements for solar energy storage in different settings. Comments are then made on the need and opportunities for 24 hr storage of electrical energy in batteries; backup systems that use stored chemical fuel derived from solar energy; storage of intermediate temperature heat as heat of hydration of compounds such as sulfuric acid; annual storage of low temperature heat in fresh water ponds or aquifers; and annual storage of ice produced in places with cold winters. Arguments are presented for using a systems approach to the selection of solar energy storage methods appropriate for use in specific types of settings.

Keywords. Appropriate technology; chemical energy; electrical energy; energy; hydration energy; ice; insolation; morphological outline; pond; storage; solar energy; thermal energy.

1. Introduction

Solar energy in this paper means any type of energy renewably derived from solar radiation. The types of solar energy considered are electrical or mechanical energy; chemically stored energy; gravitational energy in material that has been lifted; and both sensible and latent heat at temperatures that are high ($T \geqslant 500°C$), intermediate ($500°C > T \geqslant 100°C$), and low ($T < 100°C$). It is also useful to distinguish between two different categories of solar energy. 'Direct' solar energy requires human intervention in the initial absorption of solar radiation (as in thermal energy collectors, solar electric cells, or cultivation of plants). 'Indirect' solar energy involves human intervention at some point in a natural cycle *after* solar radiation has been absorbed (such as hydroelectric, wind, or wave energy).

This paper has three primary purposes. The first is to set forth a logical framework for classifying various types of solar energy storage systems. The second is to display the wide ranges of requirements for energy storage that are determined by the local availability of natural solar energy and by the local energy end-use patterns in different settings. The third is to point out a number of opportunities, constraints, and problems, associated with several specific types of solar energy storage systems. This paper should *not* be considered as a review or assessment of all major types of energy storage systems that are now available or under development.

Energy storage systems can often play important roles between the initial collection of solar energy and its conversion to the type of energy that is to be delivered for end use. Heat or chemical energy, for example, can be stored for ultimate conversion to electric power. Furthermore, two or more different types of energy may be advantageously stored sequentially in the same system. In a system for converting animal or crop wastes to biogas to electric power, for example, both the organic material and the gas could be stored to produce gas or electric power as needed.

A solar energy supply system should be appropriate for its setting. It should be adapted to the local availability of natural solar energy and to the basic energy needs of the people it serves (Reddy 1978). Energy storage components of the system, in turn, should be appropriate for the system as a whole. In general, therefore, the choice of methods for storage of solar energy within a particular system should depend on the setting's geophysical, economic, demographic, cultural, political and other characteristics.

2. Framework for classifying solar energy storage systems

There is a wide variety of different types of solar energy that can be extracted from the natural environment in different places on earth—solar radiation; kinetic and thermal energy in wind, fresh water and seawater; gravitational energy in lifted water; stored chemical energy in wild plants; osmotic energy in seawater relative to fresh water. There are also many different ways to collect such natural sources of solar energy for subsequent conversion to some useful type of energy. The best choices of methods for storage of solar energy often depend on the type of solar energy that is to be collected from the natural environment, and on the specific method used for collection.

A large number of different types of energy can be derived from natural solar energy, often from a single source. Appropriate conversion of collected solar radiation, for example, can yield electric power; dozens of different types of chemical fuels; heat at temperatures ranging from less than 100°C to nearly 6000°C; mechanical energy; and cold media that, by absorbing energy, can be used for energy management. All other types of naturally available solar energy can also be converted to each of these types of energy, although the conversion efficiencies or costs may in many cases be unacceptable.

There are many different conceivable options for storing energy in a system designed to supply any particular type of energy derived from solar energy collected by any particular type of collector. The product energy itself can generally be stored in a variety of different ways, as can any intermediate types of energy between the initial collection and final output.

In short, one can conceive of a huge number of different types of solar energy storage methods, each characterised by the nature of the setting, the final solar energy product, and the type of solar energy collection system.

Table 1 is a morphological outline that can be used to characterise a very large number of different types of solar energy storage systems. A morphological outline is a set of lists of alternative attributes, under various major categories, that are conceivable for a specific object, event, or process in some broad category, such as energy storage (Zwicky 1951). It has the property that random selection of attributes

Table 1. Morphological outline of solar energy storage systems

1. Type of setting for solar energy supply system of which storage system is a part
- 1.1 Demographic characteristics
  - 1.1.1 Urban
  - 1.1.2 Suburban
  - 1.1.3 Rural
  - 1.1.4 Not specified
- 1.2 Development stage of country
  - 1.2.1 Industrialised
  - 1.2.2 Developing
  - 1.2.3 Not specified
- 1.3 Economic category of population served by energy system
  - 1.3.1 Average per capita income $\geqslant 1/2$ national average
  - 1.3.2 Average per capita income $< 1/2$ national average
  - 1.3.3 Not specified
- 1.4 Geophysical characteristics
  - 1.4.1 Latitude
    - 1.4.1.1 Tropical
    - 1.4.1.2 Temperate
    - 1.4.1.3 Arctic
    - 1.4.1.4 Not specified
  - 1.4.2 Annual average cloudiness
    - 1.4.2.1 Sunshine $>70\%$ of maximum possible
    - 1.4.2.2 Sunshine between 30% and 70% of maximum possible
    - 1.4.2.3 Sunshine $<30\%$ of maximum possible
    - 1.4.2.4 Not specified
  - 1.4.3 Winter air temperatures
    - 1.4.3.1 Degree (C)-hours below freezing $\geqslant 2000$
    - 1.4.3.2 $2000 >$ degree-hours below freezing $\geqslant 300$
    - 1.4.3.3 Degree-hours below freezing < 300
    - 1.4.3.4 Not specified
  - 1.4.4 Warm season air temperatures
    - 1.4.4.1 Degree (C)-hours above $25°C \geqslant 20{,}000$
    - 1.4.4.2 $20{,}000 >$ degree hours above $25°C \geqslant 4{,}000$
    - 1.4.4.3 Degree-hours above $25°C < 4{,}000$
    - 1.4.4.4 Not specified
- 1.5 Setting's annual demand for energy produced by solar energy system
  - 1.5.1 10^{16} joules
  - 1.5.2 10^{14}–10^{16} j
  - 1.5.3 10^{12}–10^{14} j
  - 1.5.4 10^{10}–10^{12} j
  - 1.5.5 $<10^{10}$ j
  - 1.5.6 Not specified

2. Type of energy product of solar energy supply system of which storage system is a part
- 2.1 Radiation (e.g. visible light)
- 2.2 Electric power
  - 2.2.1 Alternating current
  - 2.2.2 Direct current
  - 2.2.3 Other
  - 2.2.4 Not specified
- 2.3 Mechanical energy
- 2.4 Chemical fuel
  - 2.4.1 Hydrogen
  - 2.4.2 Gaseous hydrocarbon (e.g. methane)
  - 2.4.3 Carbon monoxide
  - 2.4.4 Other gaseous fuel (e.g. ammonia)
  - 2.4.5 Ethanol
  - 2.4.6 Methanol
  - 2.4.7 Liquid hydrocarbon
  - 2.4.8 Other liquid fuel
  - 2.4.9 Solid carbon (e.g. charcoal)
  - 2.4.10 Cellulose
  - 2.4.11 Other solid fuel
  - 2.4.12 Not specified
- 2.5 Heat
  - 2.5.1 Type of heat
    - 2.5.1.1 Sensible
    - 2.5.1.2 Latent

Table 1 (contd.)

- 2.5.2 Temperature
  - 2.5.2.1 High ($T \geqslant 500°C$)
  - 2.5.2.2 Intermediate ($500°C > T \geqslant 100°C$)
  - 2.5.2.3 Low ($T < 100°C$)
  - 2.5.2.4 Not specified
- 2.6 Heat sink
  - 2.6.1 Cold water
  - 2.6.2 Ice
  - 2.6.3 Other
  - 2.6.4 Not specified
- 2.7 Not specified

3. Type of solar energy collection system
   - 3.1 Direct solar energy
     - 3.1.1 Pure radiation (e.g. interception and channelling of visible light)
     - 3.1.2 Photovoltaic
     - 3.1.3 Photoelectrochemical (e.g. photogalvanic batteries)
     - 3.1.4 Non-biological photochemical (e.g. photodissociation of water to hydrogen and oxygen)
     - 3.1.5 Cultivated plants
     - 3.1.6 High temperature heat ($T \geqslant 500°C$)
     - 3.1.7 Intermediate temperature heat ($500°C > T \geqslant 100°C$)
     - 3.1.8 Low temperature heat ($T < 100°C$)
     - 3.1.9 Other
     - 3.1.10 Not specified
   - 3.2 Indirect solar energy
     - 3.2.1 Kinetic energy of flowing water (not including surface waves)
       - 3.2.1.1 Fresh water (e.g. conventional hydroelectric)
       - 3.2.1.2 Sea water (e.g. extraction of energy from ocean currents)
       - 3.2.1.3 Not specified
     - 3.2.2 Thermal energy of natural water bodies
       - 3.2.2.1 Thermal energy in fresh water (e.g. upper strata of deep lakes)
       - 3.2.2.2 Ocean thermal energy (e.g. upper strata of tropical oceans)
       - 3.2.2.3 Not specified
     - 3.2.3 Kinetic energy in wind
     - 3.2.4 Thermal energy in air (e.g. low humidity air used for drying)
     - 3.2.5 Renewable solar thermal energy in natural bodies of earth or rock
     - 3.2.6 Surface wave energy
       - 3.2.6.1 Fresh water bodies (e.g. large lakes)
       - 3.2.6.2 Ocean
       - 3.2.6.3 Not specified
     - 3.2.7 Osmotic energy in sea water, relative to fresh water
     - 3.2.8 Wild plants
     - 3.2.9 Other
     - 3.2.10 Not specified
   - 3.3 Not specified

4. Type of storage
   - 4.1 Type of energy stored
     - 4.1.1 Same as energy product of solar energy system (same breakdown as used under outline category 2 used for 4.1.1, 4.1.2, and 4.1.3)
     - 4.1.2 One type of energy stored at intermediate stage between collection and product
     - 4.1.3 Two or more types of energy stored at intermediate stage between collection and product
   - 4.2 Storage capacity
     - 4.2.1 Ratio of energy storage capacity to total energy required to sustain *annual* output of specified type of energy from solar energy system
       - 4.2.1.1 >90%
       - 4.2.1.2 50–90%
       - 4.2.1.3 10–50%
       - 4.2.1.4 2–10%
       - 4.2.1.5 0.4–2%
       - 4.2.1.6 0.1–0.4%
       - 4.2.1.7 <0.1%
       - 4.2.1.8 Not specified
     - 4.2.2 Characteristic storage time corresponding to less than 20% loss of stored energy
       - 4.2.2.1 >1 year
       - 4.2.2.2 6 months–1 year
       - 4.2.2.3 1 month–6 months

Table 1. (Contd.)

4.2.2.4 1 week–1 month
4.2.2.5 24 hours–1 week
4.2.2.6 5 hours–24 hours
4.2.2.7 Less than 5 hours
4.2.2.8 Not specified

4.3 Range of capital costs, per unit storage capacity, of fabricated equipment and materials that are not produced at the site of the storage systems, in Rs/10^9 j of storage capacity (assume 1 U.S. dollar=8 Indian rupees)

4.3.1 $>10^5$
4.3.2 10^4–10^5
4.3.3 10^3–10^4
4.3.4 10^2–10^3
4.3.5 10–100
4.3.6 1–10
4.3.7 <1
4.3.8 Not specified

4.4 Range of labour person-hours, per unit storage capacity, required for on site construction and assembly of storage system (person-hours/10^9 j of storage capacity).

4.4.1 >1000
4.4.2 100–1000
4.4.3 10–100
4.4.4 1–10
4.4.5 0.1–1
4.4.6 <0.1
4.4.7 Not specified

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in each category in the outline must yield a subject that makes logical sense, whether or not it corresponds to something that exists or is practical or even interesting. As long as this property is strictly maintained, the major categories or sub-categories can be chosen arbitrarily. The choices depend on the features of the subject that are to be emphasised and the level of detail desired in the breakdown of the subject.

The number of different types of energy storage systems that can be specified by table 1 is of the order of ten billion (10^{10}) if only *one* type of energy is stored in each system. It might be argued that most of the permutations possible with such outlines are trivial or completely impractical. But one must be careful about the word 'most', since, for example, 1 % of ten billion is still a very large number. Furthermore it is easy to expand table 1 to include many further subdivisions that are far from trivial. The outline, for example, does not distinguish between specific methods for storing each kind of energy (e.g. different heat storage media or basically different types of batteries). Yet, permutation of the components of category 4 of the outline (type of storage) yields nearly 2000 different possibilities, not including differences in the setting, type of energy system product, or type of collection system. In spite of the very large number of systems that can be specified by table 1, the author has found that random selection of subcategories of the outline as a whole tends to yield possibilities that cannot be dismissed out-of-hand as trivial or uninteresting.

Several conclusions can be drawn from table 1:

(i) Solar energy storage is an extremely complex subject.

(ii) A morphological outline along the same general lines as table 1 could be used as a logical framework for organising an information storage and retrieval system that contains information concerning solar energy storage technology.

(iii) A logical and application-oriented way to select a specific type of solar energy storage system for detailed consideration is *first* to specify the types of settings, energy products, and solar energy collection systems to which energy storage may be relevant, and *then* to search for energy storage concepts that are most appropriate. This approach is more likely to focus attention on appropriate solar energy storage technologies than starting with analyses of each of the major storage technologies that are now available or under development. The spirit of this approach is to ask: ' What do I need?' before asking: ' What does technology have to offer me?' If the answer to the second question is that what is needed is not likely to be available within an acceptable time, then it may be necessary to make compromises in the statements of needs for storage. Under some conditions, for example, it may be advantageous to modify the energy use patterns in a particular setting, or shift to a different type of solar energy collection system that is more compatible with available storage technologies.

3. Coupling between solar energy availability and storage needs

The needs for storage of solar energy are set by the relationships between the instantaneous availability of natural solar energy and the demand for energy in a particular setting. Even if the rate of collection and conversion of some type of solar energy can be essentially constant all year (as is nearly the case for systems for producing electric power from ocean thermal gradients in some tropical locations), energy storage may be required if the *demand* for energy from the system is not constant. In this case the need for storage might be avoided if the energy supply system's peak power capacity is equal to the annual peak demand for power. The annual average load factor of the generating plant (the ratio of energy produced per year to the energy that would be produced if the plant operated at full capacity all year) however, may then correspond to unacceptably high capital cost contributions to the cost of delivered energy.

All direct solar energy systems require some storage capacity unless the rate of demand for energy is always less than or equal to the highest rate of energy production that is compatible with the instantaneous insolation (the rate of incidence of solar radiation per unit area). Most indirect solar energy systems have a similar property if the analogue of the instantaneous insolation is taken to mean the rate of collection of energy (such as kinetic energy of wind or gravitational energy of water collecting in a reservoir behind a dam). In either case, energy demand patterns that follow the instantaneous availability of natural solar energy may sometimes be reasonable. At some low value of the capital cost of a facility for using electricity or high temperature heat for an industrial process, for example, it might be advantageous to use a solar energy system without storage to supply the needed energy. Refining of some primary metals, such as aluminium, might be in this category. But such situations can be expected to be relatively rare.

Much can be learned about the relative needs for solar energy storage in different regions by studying their insolation patterns. Table 2 presents estimates of various measures of insolation at six specific locations (Taylor 1979). These locations correspond to the largest and the smallest reported values of the annual average total horizontal insolation within three bands of latitude (including both northern and

Table 2. Global insolation summary

Insolation data	Marigat, Kenya (0°35′N)	Benin City, Nigeria (6°33′N)	Adrar, Algeria (27°52′N)	Tomei, Japan (32°37′N)	Prosser, Wash., USA (46°10′N)	Bochum, FR Germany (51°29′N)
Total horizontal (direct plus scattered)						
Annual average (W/m²)	312	170	260	110	194	91
Minimum monthly average (W/m²)	251	139	160	61	50	14·5
Maximum monthly average (W/m²)	338	194	339	144	343	173
Lowest 4 month total/annual total	0·31	0·30	0·24	0·26	0·12	0·090
Maximum daily average (W/m²)	342	342	380	385	384	380
Total, fixed tilt at latitude angle						
Annual average (W/m²)	312	170	265	102	220	85
Minimum monthly average (W/m²)	251	140	217	67	96	20
Maximum monthly average (W/m²)	338	200	286	144	325	170
Lowest 4 month total/annual total	0·31	0·30	0·28	0·30	0·16	0·13
Maximum daily average (W/m²)	342	342	310	320	330	340
Direct horizontal						
Annual average (W/m²)	258	77	194	37.4	139	33·5
Minimum monthly average (W/m²)	175	52	116	17·5	26·1	3·3
Maximum monthly average (W/m²)	287	97	261	73·4	280	67·6
Lowest 4 month total/annual total direct	0·30	0·26	0·23	0·27	0·089	0·060
Maximum daily average (W/m²)	290	290	320	330	330	320
Direct normal						
Annual average (W/m²)	360	110	310	62	240	60
Minimum monthly average (W/m²)	200	60	230	40	100	17
Maximum monthly average (W/m²)	380	130	350	120	430	100
Lowest 4 month total/annual total direct	0·26	0·22	0·25	0·35	0·15	0·12
Maximum daily average (W/m²)	385	385	430	460	510	510

southern latitudes): 0°–20°; 20°–40°; and 40°–55° (Löf *et al* 1966). On an annual average basis, Marigat, Adrar and Prosser represent the sunniest, and Benin City, Tomei, and Bochum, the cloudiest regions in each of the three latitude bands. The indicated values of all insolations except total horizontal should be used with caution, since they have been estimated by using some empirical rules of thumb that may lead to errors as large as a factor of two for direct normal and indirect horizontal

insolations in the cloudiest regions. The direct normal insolations apply to tracking and focussing collectors.

The minimum monthly average insolations in regions near the equator are during the cloudiest part of the season, not necessarily in winter. At the other four locations at higher latitudes, the minimum monthly average is in midwinter, and the maximum is in midsummer. The maximum daily average figures, at all locations, are for unusually clear days during the period of highest insolation.

A perusal of table 2 suggests the following rather broad conclusions that relate to the needs for solar energy storage in different climatic regions:

(i) At high latitudes, the capacity to store solar energy collected during periods of high insolation for six months or more, for delivery in winter or to meet a more or less constant load demand all year, dramatically increases the total annual useful energy collected per unit area of collector. In Bochum, Germany, for example, the area of a tilted collector required to intercept a given amount of energy for use in the four coldest months, without long term storage, is about eight times the area required for a *horizontal* collector with long term (eight month) storage. If account is also taken of the lower *efficiency* of collectors of solar heat during periods of relatively low light intensity, the relative collector area required in the two cases favours a long term storage system by a factor as high as about 15.

(ii) Variations in the annual quantity of solar energy intercepted by the same collector area in different locations at roughly the same latitude can be as large as a factor of three, as a result of differences in average cloudiness.

(iii) Fully tracking, focussing collectors intercept about two-thirds or less total usable radiation per year in very cloudy regions than horizontal or fixed, tilted collectors that also collect diffuse radiation, but do not focus the light.

(iv) The increase in winter insolation on a collector tilted at an angle equal to the local latitude, compared to a horizontal collector, is less than a factor of two at very high latitudes under all cloudiness conditions, and is much less than a factor or two at lower latitudes.

(v) The total annual insolation on a tilted collector is nearly the same, at all locations, as on a horizontal collector.

(vi) The seasonal variations in the monthly average global insolation rates in the equatorial regions are less than about 40%, compared with as much as a factor of 12 at high latitudes.

(vii) The seasonal variations in the monthly average direct normal (focussable) insolation in the equatorial regions are typically about a factor of two, compared with as much as a factor of 6 at high latitudes. Note that seasonal variations in global insolation are smaller than those in direct normal insolation near the equator, while the reverse is the case at high latitudes.

(viii) The maximum daily average total insolation on a horizontal or fixed, tilted surface on an unusually clear day is nearly the same at all locations (about 350 ± 35 W/M^2). This means that energy storage capacities required to maintain an approximately constant energy output during the sunniest 24 hr periods will not vary dramatically from one region to another, if both direct and diffuse radiation are being collected. Focussing collectors, on the other hand, collect as much as 32% more energy on the sunniest days at high latitudes than near the equator, since the sun is above the horizon for a longer fraction of a 24 hr period.

These eight conclusions all support the overall conclusion that the characteristics

of collectors and storage systems appropriate for different specific climatic settings are likely to differ widely.

Although the area of collectors required for some purposes may be smaller, in some regions, if the collectors are tilted than if they are horizontal, the horizontally projected total surface area required for arrays of tilted collectors that are close enough to each other to shadow each other significantly is at least as large as for horizontal collectors. In other words, tilting non-focussing collector arrays may save collector area under some conditions, but can never save land area, and can often waste it. This observation does not hold, however, for collectors that are spaced sufficiently far apart to avoid overlapping shadows (e.g., roof-top collectors on buildings separated by distances somewhat greater than their heights).

4. Comments on methods for storing different types of solar energy

4.1. *Electrical energy*

Rechargeable battery or fuel cell storage of electrical energy can now be economically attractive for overnight storage, but is unlikely to become economical for storing a large fraction of the annual output of a solar electric system, by means that are now conceivable. The storage capacity required to be able to supply a constant electric power output for 24 hr during which the day-time insolation is the maximum possible (on a clear day in summer) is between 4 and 5 kWh per kW of steadily delivered power. The present US costs of lead-acid batteries correspond to about Rs 600/kWh of storage capacity, which corresponds to Rs 2400 to Rs 3000 per kW of steady power output. This, in turn, corresponds to less than Rs 0.08/kWh of power delivered by a system with 24-hr battery storage. But costs of storage increase sharply if sufficient storage is supplied to maintain a steady power output during extended periods of cloudy weather. The costs of sufficient storage to maintain a roughly constant average daily output of electric power all year in regions with low winter insolation are clearly unacceptable with any type of battery or fuel cell system that is now under development, unless the primary electric power output from the solar-electric power system is maintained at the low value that corresponds to the average insolation in winter.

An attractive alternative to providing battery storage of electric power for extended periods, but for total times that are much shorter than a year, is to use a chemically fuelled back-up system having a low capital cost per unit of rated output, even if the fuel cost is relatively high. The chemical fuel could either be one that is derived renewably from solar energy (such as methane or alcohol derived from biomass, or hydrogen or other fuels produced electrolytically by solar-electric power) or a fossil fuel. Suppose, for example, that the back-up system is a gas turbine costing Rs 1,600 per rated kW of output; the fuel cost is Rs. $40/10^9$j; the total annual power output from the back-up system is 25% of the annual power output from the entire system; and the efficiency of the turbine-generator is 35%. The cost of back-up power would then be Rs 0.50/kWh of which Rs 0.40/kWh would be fuel costs. If the cost of power from the primary system were greater than this, use of the back-up system would obviously lower the overall costs of power. If the cost of power from the primary system were substantially less than Rs 0.50/kWh use of the back-up system would

add only about Rs 0.12/kWh to the overall cost of power. This added cost would be proportionately lower if the back-up system provided less than 25% of the annual power output.

4.2. *Chemical fuels*

Storage costs of solid or liquid chemical fuels derived from solar energy are much lower than storage costs of other forms of solar energy or the costs of making the chemical fuels themselves. The cost of storing large fractions of the gaseous fuel output of a solar energy system, however, can be a major part of the total system cost if the gas is liquefied or stored at high pressure in fabricated containers. Low-cost storage of gaseous fuels, such as methane, is possible slightly above normal atmospheric pressure inside plastic film bubbles of sufficient size. But this type of storage can be hazardous and unreliable.

4.3 *Heat*

It is easy to show that the only materials that could be used economically to store heat for most of a year are water or onsite earth or rock. The material costs of all other possible liquid or solid heat storage media, such as oil, industrial chemicals, or rock transported a significant distance to the site exclude their use for such long-term heat storage. Rock delivered to a site at Rs 80/ton, for example, would contribute a cost of about Rs $30/10^9$ j of energy stored for a year, if the stored heat corresponded to a temperature rise of 300°C. This estimate is based on a capital charge rate of 10% per year. This does not include the cost of any container or insulation. Oil, at a cost of Rs 120/barrel, would contribute a cost of about Rs $120/10^9$j of annually stored heat energy, if its temperature were 300°C above room temperature. Storage of heat at lower temperatures would increase the cost of heat storage proportionately. Water priced at Rs $1.0/M^3$, on the other hand, would contribute about Rs $0.6/10^9$j of annually stored heat, assuming a useful temperature difference of 40°C for the water.

Possibilities for long-term storage of heat in hot water or the ground have received surprisingly little attention. Possible approaches to low-cost containment of heat in bodies of water include the use of nearly stagnant subsurface aquifers (Anon 1979) or hot water storage ponds of sufficient depth and breadth so that heat losses to the adjacent ground are acceptable (Williams 1975). Heat losses from the surface of hot water ponds can be sharply reduced by covering them with air inflated transparent plastic mats which, during periods of high insolation, allow the ponds to be used as solar collectors (Taylor 1978). It may be necessary to fill such covers with detergent foam, similar to that used for fire fighting, to reduce heat losses at night in winter or during extended periods of cloudy weather. Such heat storage reservoirs are not likely to be economical for storing heat for space heating or other uses by individual households or small commercial or industrial enterprises, because of excessive heat loss or costs of insulation. The bottom and sides of storage reservoirs large enough to supply space heat or hot water for several dozen or more households, however, can be adequately insulated by the adjoining ground itself. The water in such a pond can be kept from seeping into the ground by lining it with plastic film, a technique that is now used for artificial fresh water reservoirs. Costs of hot water storage ponds or underground aquifer storage reservoirs are uncertain, but there are no basic reasons

to expect the costs per unit of energy storage capacity to rule them out for long-term heat storage.

An increasing variety of intermediate-to-high temperature heat storage media become economical as the storage time decreases from months to weeks to hours. Of particular interest are what are sometimes called ‘ room temperature ’ heat storage media that require little or no insulation because the ‘ heat ’ is reversibly stored in two substances that release heat when mixed, but can be separated by the application of heat. An example is sulfuric acid and water (Huxtable & Poole 1976). When concentrated sulfuric acid is mixed with water, the mixture's temperature can rise above the boiling point of water. If the diluted mixture is stored after the heat of mixing has been transferred for some use, the mixture can later be re-concentrated by using solar heat when it is available. Such systems are actually chemical storage systems whose thermal and chemical energy contents can be reversibly changed by the application or withdrawal of heat. The costs of such substances probably make them uneconomical for annual storage, but may be acceptable for storage up to several months.

4.4 *Ice*

Stored ice can be a valuable part of a solar energy system used for space cooling, refrigeration, or lowering the low temperature side of a heat engine. The latter makes it possible to extract more mechanical work or electric power from an engine. Lowering the low temperature side of an engine a given number of degrees increases the power output more than increasing the hot side temperature by the same amount. The heat of melting of ice is such that it can absorb the same amount of heat as corresponds to an 80°C temperature rise in liquid water. The cost of storage of a given capacity to absorb heat in ice is likely to be less than the cost of storing the same capacity to release heat in hot water. This results from the high heat of melting ice and the fact that convection cannot transfer heat *downward* from warm air above the surface of an insulating layer on top of the ice reservoir.

In places with sufficiently cold winters large quantities of ice can be produced by keeping air below freezing temperatures in contact with the surface of a pond over which unfrozen water is spread periodically (Taylor 1978). Approximately one meter of ice can be produced for every 1000 degree (centigrade)-hours that the air temperature is below freezing. In many parts of the world at high latitude or high altitude, such as most of the northeastern United States or the Himalayas, the number of degree-hours below freezing each winter is several thousand. Thus, in such areas, ice ponds several meters thick can be frozen in winter, and the ice stored for subsequent use throughout the year. Preliminary estimates by the author (Taylor 1979) suggest that it may be economically attractive to transport ice slurries via covered aqueducts from cold regions at high elevations to lower, warmer regions 1000 km or more away from the ice ponds.

5. Conclusions

This paper has pointed out the huge variety of ways that solar energy can be stored to serve many kinds of purposes in many different types of settings. The paper has

also demonstrated that the choice of the most appropriate type of storage system to use in a specific type of setting depends on a large number of factors related to the nature of the setting, the type of energy needed, and the technological alternatives for satisfying the energy needs with solar energy. This choice should therefore be made in the context of overall analyses and assessments of complete solar energy systems designed to be most appropriate for each type of setting.

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Cooking at low temperatures: energy and time requirements

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Abstract. A flat plate solar collector can easily supply hot water at temperatures upto 90–95°C. At these temperatures, rice, potatoes and vegetables can be cooked without much difficulty. However, to design an efficient solar system for cooking, one must know the exact energy and time required for cooking at these temperatures. Our experiments show that the actual energy consumed in cooking rice, potatoes or green vegetables is only 0·06 to 0·10 kWh/kg at cooking temperatures of 82–88°C and the cooking time at these temperatures is 30–45 min.

Keywords: Solar energy; cooking temperatures; solar cookers; solar thermal applications; cooking energy.

1. Introduction

In recent years, solar cookers of various types, such as the concentrator or box type, have been designed and demonstrated. While the feasibility of cooking with solar energy has been well established, no data have been reported so far about the exact energy and temperature requirements of cooking various cereals. Such information is important in designing efficient solar systems for cooking. This paper reports the results of experiments for determining the energy and temperature requirements for cooking rice, potatoes and green vegetables.

2. Experimental set-up

The experimental set-up is shown in figure 1. It consists of an aluminium cooking vessel of 210 mm diameter and 220 mm height. The vessel is heated by a 1 kW electric hot-plate placed underneath the container. The losses from the vessel to the surroundings are minimised by using 60 mm thick mineral wool insulation on the sides and 150 mm thick mineral wool insulation at the bottom. The top of the vessel is covered with a 25 mm thick wooden slab to prevent evaporation losses and to keep the conduction losses to the minimum. Appropriate holes are provided in the wooden slab for inserting a thermometer and for taking out samples.

An energy meter is connected in circuit with the heater to measure the energy input. The heater is switched on or off manually by observing the temperature in the container. The on or off condition of the heater is indicated by a lamp.

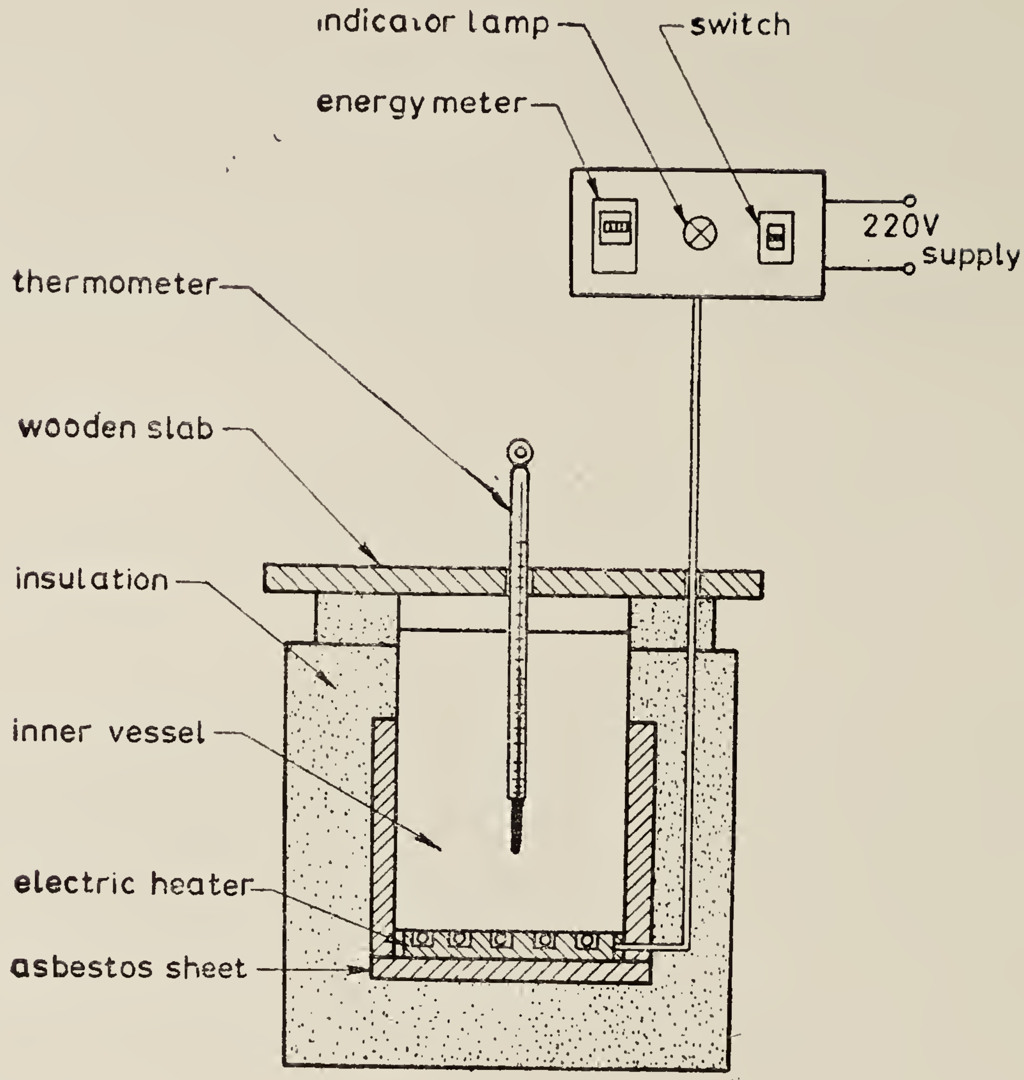

Figure 1. Experimental set-up.

3. Procedure

The experimental procedure used to determine the energy and time requirements for cooking is described below. An energy balance for the experimental set-up is as follows:

Energy consumed in cooking
= (Energy input to the electrical heater)
— (Increase in the sensible heat of water) (1)
— (Energy loss to the surroundings).

The energy input to the electrical heater is directly measured with the help of an energy meter. The increase in the sensible heat of water can be calculated from the measured temperature rise and the known quantity of water. The energy loss to the surroundings depends on the temperature difference between the vessel and the ambient, and has to be determined experimentally. For this purpose, experiment I is carried out. In this experiment only water is heated to the desired temperature and the energy loss is determined as explained later.

In experiment II, potatoes, rice and green vegetables are cooked in the vessel. By subtracting the losses to the surroundings and the increase in the sensible heat of water, the energy required for cooking is determined.

3.1. *Experiment I*

The vessel was filled with 4·82 kg of water and was heated to 85°C by switching on the heater. The heater was switched off when water temperature reached 77°C.

The temperature of water was noted down every 5 min. The energy loss to the surroundings, which includes change in the sensible heat of insulation, was computed using the following equation.

Energy loss to the surroundings = (Energy input to the electrical heater) — (Increase in the sensible heat of water ($mS\triangle t$)). (2)

The energy loss to the surroundings, the energy input and $mS\triangle t$ are plotted against time in figure 2. It is seen from the figure that there is a rapid increase in temperature when the heater is switched on. After the heater is switched off, the temperature of water still continues to rise. This is because of the heat transfer from the base which remains at a higher temperature for some time.

The temperature of water reaches a maximum, remains more or less constant for some time and then starts falling at a constant rate. The rate of fall of temperature is 0·06°C/min. This rate of cooling is found to be independent of temperature.

3.2. *Experiment II*

As seen from the results of experiment I, water continues to gain additional energy from the base even after switching off the heater. The amount of energy so gained would be difficult to determine if potatoes are also cooked simultaneously. To avoid this difficulty the following procedure is adopted. Water (3·85 kg) is put in the cooking vessel and heated by switching on the heater. The heater is switched off when the desired temperature is reached. The temperature of water first continues to rise and then slowly decreases. When the temperature again reaches the desired

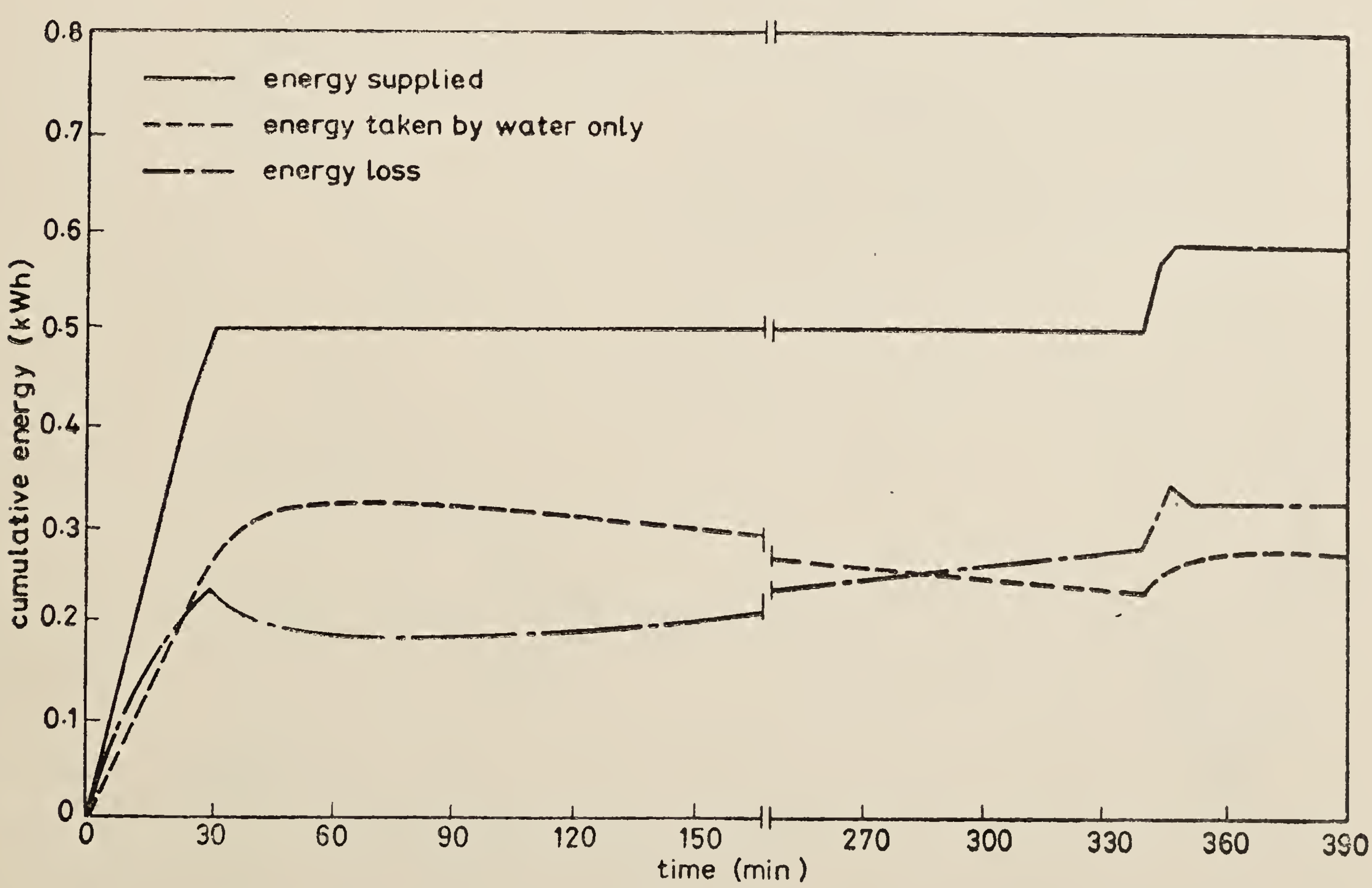

Figure 2. Energy loss from cooking vessel

value, potatoes (1 kg) are put in the vessel. The temperature of water is maintained at a more or less constant value by switching the heater on and off. The temperature is noted every 5 min till the potatoes are cooked.

The rate of energy loss to the surroundings is determined from figure 2. The energy consumed in cooking potatoes is then determined from equation (1).

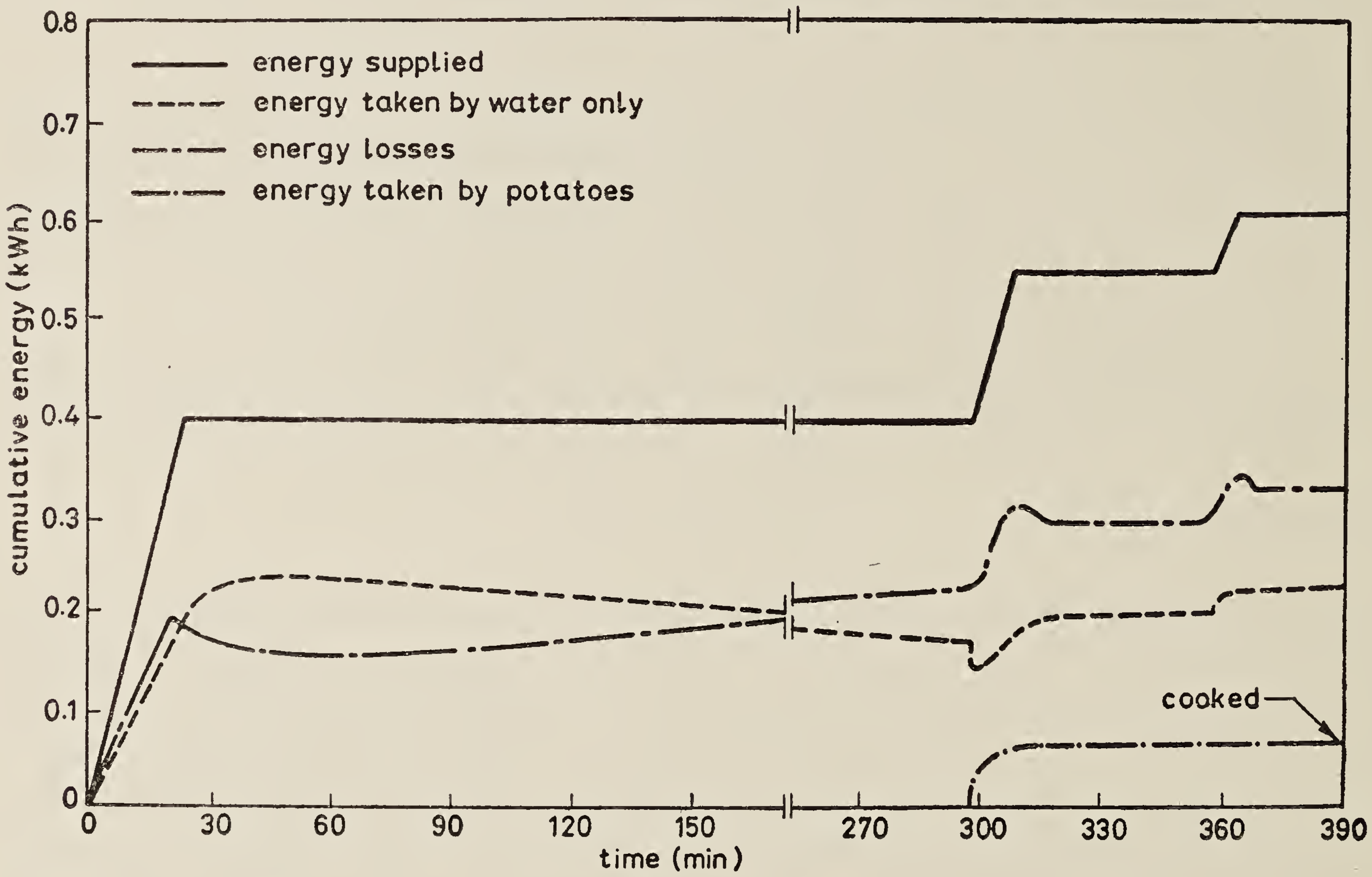

Figure 3. Energy requirements for cooking potatoes at 80–82°C.

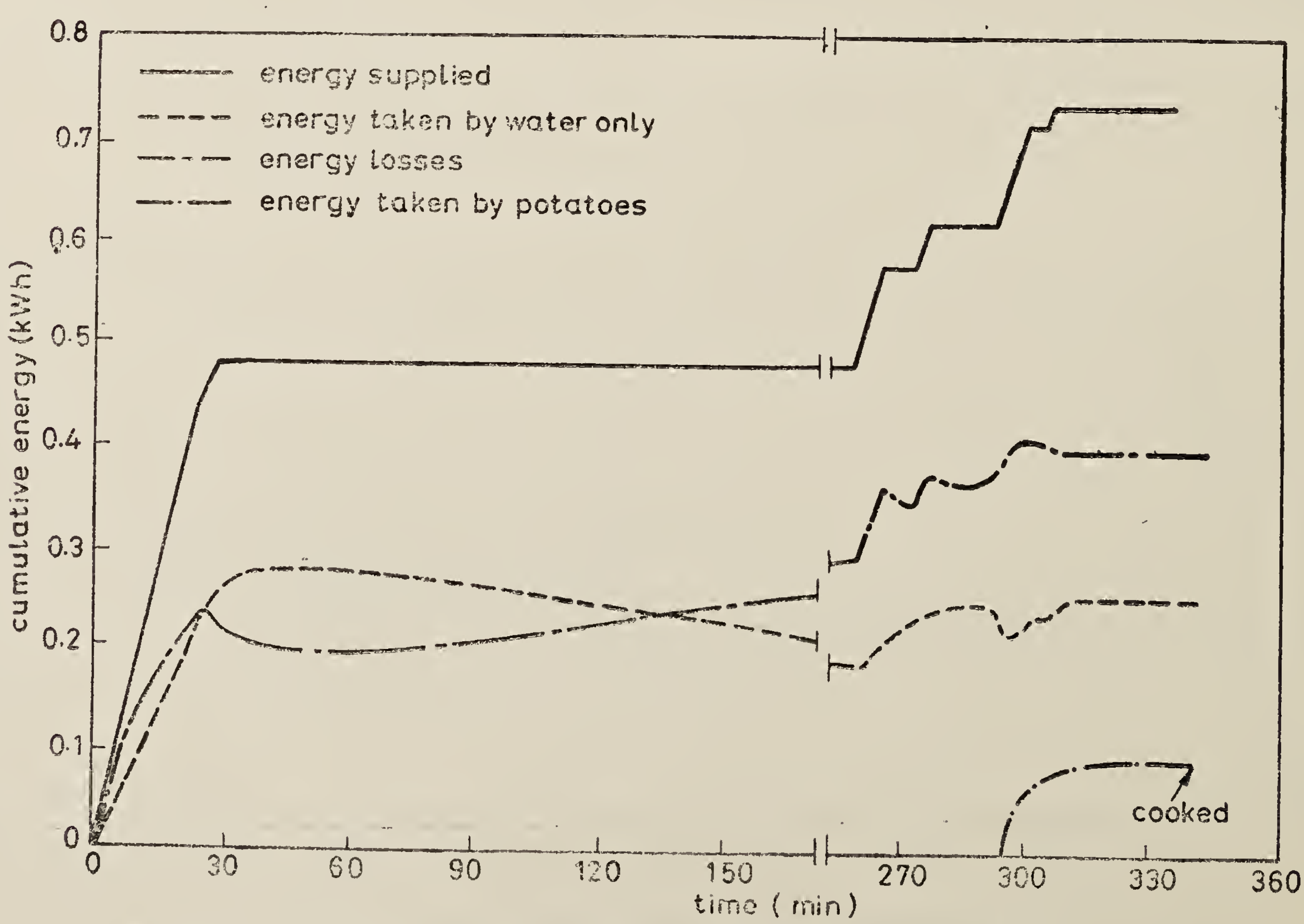

Figure 4. Energy requirements for cooking potatoes at 85–87°C.

4. Results and discussion

In figure 3, the energy input, the increase in the sensible heat of water, the energy losses to the surroundings, and the energy consumed in cooking potatoes at 80–82°C, are plotted against time. Similar results obtained at 85–87°C are presented in figure 4. The temperature of water is plotted against time in figure 5 for these two cases.

It is seen from these figures that potatoes need 0·06 to 0·09 kWh/kg for cooking. The energy required for cooking at 80-82°C is 0·06 kWh/kg as against 0·09 kWh/kg required at 85–87°C, but the cooking time is 105 min at 80–82°C as against only 45 min at 85–87°C. The energy required for cooking potatoes is approximately equal to the increase in sensible heat of an equal weight of water when the water is heated to the cooking temperature.

In experiments with rice and green vegetables (cabbage), the temperature distribution was very non-uniform. This is because the heat is transferred within rice or cabbage to a large extent by conduction, and rice and cabbage are bad conductors of heat. The rice and cabbage were stirred to increase the uniformity of temperature

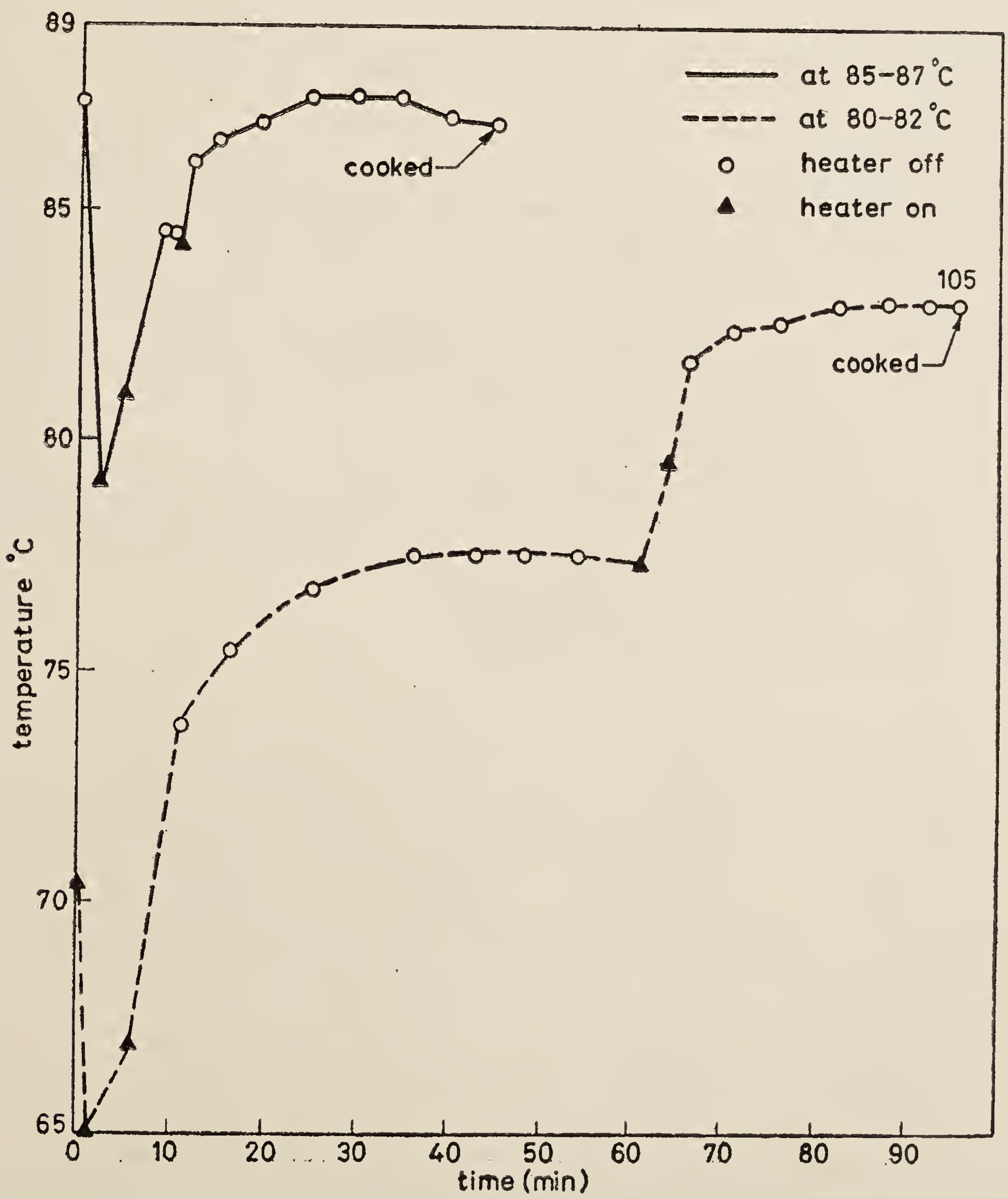

Figure 5. Temperature versus time for cooking potatoes at 80–82 and 85–87°C

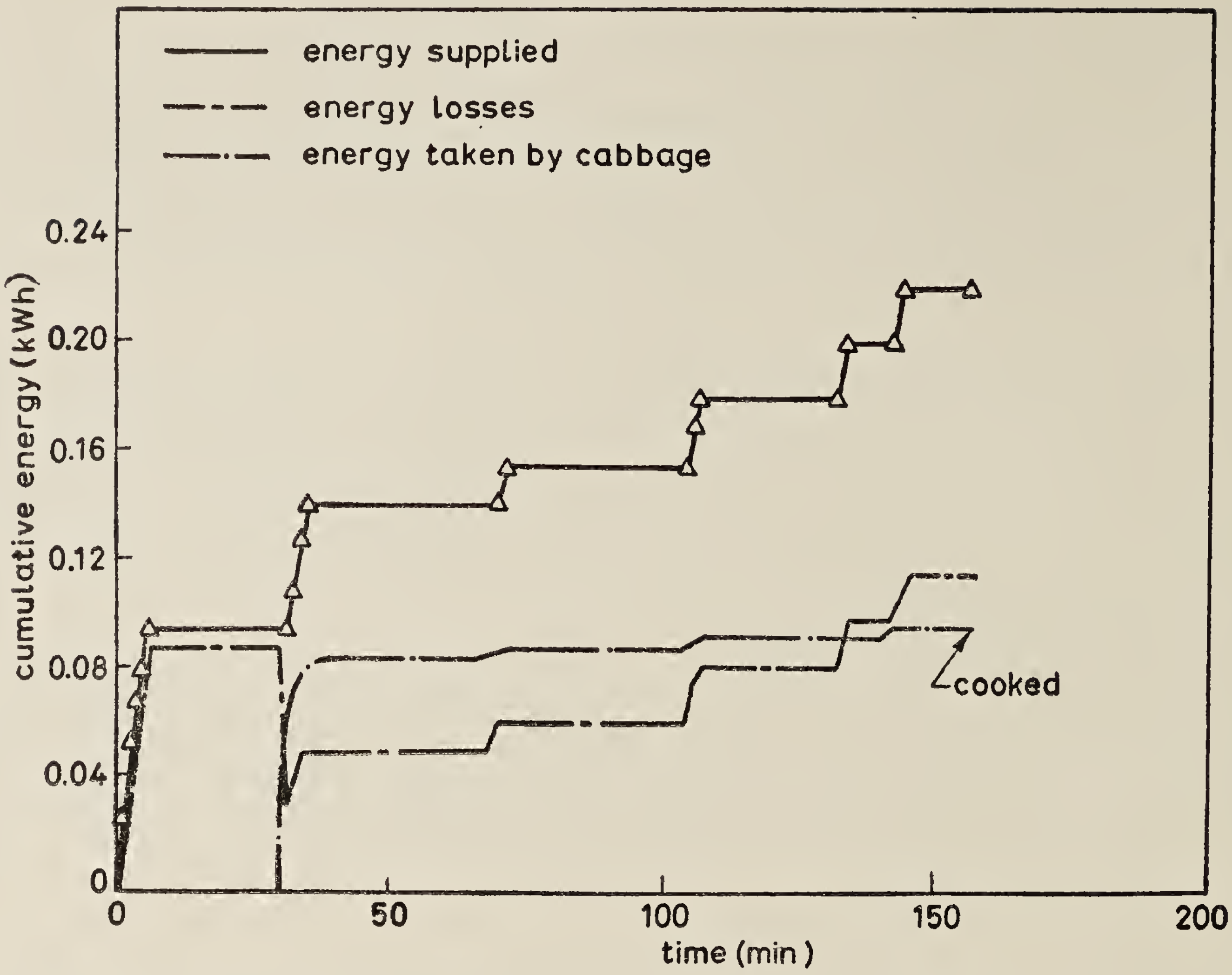

Figure 6. Energy requirements for cooking cabbage at 75–88°C

distribution. But, temperatures in rice still varied from 76°C in top layer to 98°C in the bottom layer. In cabbage the temperature varied from 82°C to 88°C. Because of the non-uniformity of temperature distribution, determination of the increase in the sensible heat of water and the energy loss to the surroundings was difficult. Therefore, in these cases, the increase in sensible heat of water as well as the energy loss to the surroundings are assumed to be the same as in experiments with potatoes at more or less the same temperatures.

Potatoes and rice have a similar chemical composition and are therefore expected to require the same energy for cooking. The results obtained following the above procedure give the same values of cooking energy for potatoes and rice. This justifies the procedure which has been adopted here.

The results obtained are tabulated in table 1.

Table 1. Cooking energy and time for potatoes, rice and cabbage.

Item	Cooking temperature (°C)	Cooking time (min)	Cooking energy kWh/kg
Potatoes	82	105	0·06
Potatoes	87	45	0·09
Rice	76–98*	30	0·08
Cabbage	82–88*	45	0·10

*The temperature distribution is non-uniform across the mass of rice and cabbage. The values given are the lowest and highest ones measured.

5. Conclusion

The following conclusions can be drawn from the results obtained about the energy and time requirements for cooking rice, potatoes and green vegetables.

(i) Rice, potatoes and green vegetables can be cooked in a reasonable time of 30 to 45 min at temperatures of 80–90°C.
(ii) The energy required for cooking rice, potatoes or green vegetables is about 0·06 to 0·10 kWh/kg.
(iii) The energy required for cooking is approximately equal to the increase in sensible heat of the same amount of water when it is heated to cooking temperature.
(iv) The energy required for cooking increases a little with the increase in cooking temperature but the cooking time is considerably reduced.
(v) The energy required for cooking rice and potatoes is almost the same but cabbage needs a little more energy.
(vi) It is feasible to use a solar hot water system using flat plate collectors for cooking rice, potatoes or green vegetables, since these can be cooked in a reasonable time at easily obtainable temperatures of 80–90°C. A cooking scheme based on a solar hot water system can be worked out as follows. Hot water at 80–90°C, instead of cold water, is poured into the jacketed cooking vessel. The material to be cooked is then added. This lowers the overall temperature. The additional sensible energy necessary to raise this temperature to 80–90°C, as well as the cooking energy, is supplied by hot water circulating through the jacket. All this energy can be supplied by a solar hot water system. Presently, the first part of the scheme, i.e. using hot water from the solar system in the cooking vessel, has been found to lead to substantial savings in the fuel used for cooking in the Jyoti Canteen.

Studies on sky-therm cooling

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Abstract. Passive cooling by the sky-therm technique presents a very attractive prospect for environmental conditioning in India because of its inherent simplicity and low cost. Sky-therm control has been proposed for storage rooms for the sericulture industry (which is a major cottage industry in Karnataka State). The temperature within these rooms is to be kept at 25 ± 3°C throughout the year. A thermal model for buildings equipped with roof ponds and movable insulating covers as proposed in the sky-therm process has been developed. The thermal behaviour of a building has been simulated to study the influence of such parameters as the heat capacity, depth of water in the pond, roof thickness and its thermal conductivity, air infiltration rates etc. Experiments have been carried out to check which of the several commonly used empirical relations for the sky temperature is valid. A simple technique for measuring air infiltration has been developed. It has been found that even for the most severe cooling requirement in Bangalore (for April), sky-therm cooling alone is adequate to maintain a temperature below 28°C. In places where the requirements are more demanding, it may be necessary to augment sky-therm with evaporative cooling.

Keywords. Sky-therm; passive air conditioning; sericulture; building; thermal analysis; nocturnal cooling.

1. Introduction

In a tropical country like India, for most part of the year, buildings and other structures are subjected to severe solar irradiation during the day. Except for a short period in winter, in almost every part of India, some means of cooling is necessary for maintaining the temperature inside such structures within either the human comfort zone or within some other given range of temperatures for other applications such as storage of silk worm cocoons and for the rearing of silk worms in sericulture industry etc. Conventional methods of airconditioning, however, need the rather scarce resources of electricity or fossil fuels. It is therefore logical to consider the use of the abundant solar energy, whose incidence is, in fact, the highest just when maximum cooling is necessary. Many solar airconditioning methods have been suggested, of which the most commonly tried technique relies on the vapour absorption cycle (Duffie & Beckman 1974). The high cost and the need for large areas of collection of solar energy are just two of the reasons why such systems are not in general use yet. On the other hand, passive methods of cooling which do not need any complex devices

A list of symbols appears at the end of the paper.

for their operation hold a better prospect for immediate application, because of their lower cost and inherent simplicity.

One of these passive methods of cooling and/or heating of buildings relies on the 'sky-therm' process first demonstrated successfully by Hay & Yellott (1968). Cooling by evaporation of water is quite well-known and has been exploited widely. However, the potential of the cold night sky in less humid areas for cooling has not been exploited so often. The sky-therm technique depends on nocturnal radiation to the sky from a roof pond for cooling the building as shown schematically in figure 1. This method requires the use of a movable insulating cover to keep out solar radiation during the day from the roof pond containing water, which loses its heat at night by nocturnal radiation when the insulating cover is removed. The cooled water in the pond can now absorb heat from the building during the day. The same system can be operated in reverse during winter by covering the pond during the night and exposing it during the day to heat the water in the pond.

In this paper, a specific application of the sky-therm process for cooling of rooms used for storage of cocoons and rearing of silk worms is considered. For ensuring a high quality and a high yield of silk, the optimum temperature within the rooms should be within 25±3°C. Most of the mulberry silk produced in the state of Karnataka (where about 88% of India's silk is produced) comes from small-scale cottage industries. Hence an inexpensive, relatively unsophisticated and simple interior cooling device is desirable for this industry. The thermal and moisture load imposed by the cocoons is very modest and it is thus conceivable that the passive method of cooling that uses sky-therm alone or evaporative cooling in conjuction, could be adequate for the control of temperature within the temperature limits specified, even during the hottest period in the year. In this context, it may also be noted that the humidity levels are not high over most parts of Karnataka where

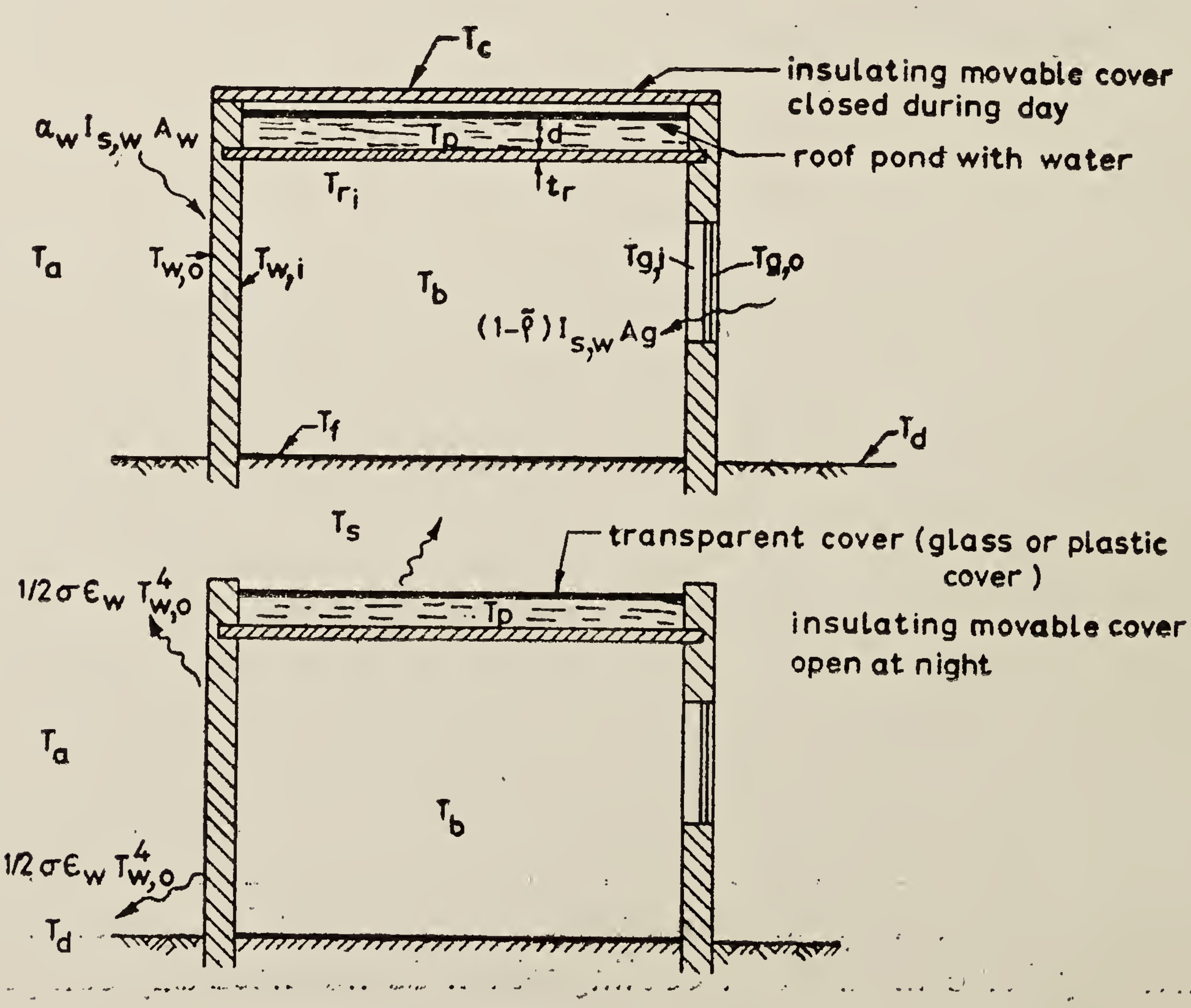

Figure 1. Schematic for sky-therm cooling in summer. (In winter, when heating is required, the movable cover is opened during the day and closed at night)

the sericulture industry is located during the summer months when cooling is most essential.

A full-sized family house located in California, USA, has been heated and cooled throughout the year as a demonstration of the utility of the sky-therm technique. Sealed transparent plastic bags containing water placed on the roof equipped with movable insulation were able to maintain the interior of the house within 19 to 24°C for the duration of test over most of the year while the ambient temperatures varied from about 8 to 32°C (Niles 1976). An experimental low cost building with a roof pond has been built on the Indian Institute of Science campus and some preliminary experiments on cooling were conducted on it.

As a first step in the design of a passively cooled or heated building a thermal model has been developed. The thermal behaviour of the structure is simulated by using a simple thermal network consisting of points (representing the temperatures of locations both inside and outside the building) such as T_a, $T_{w,o}$, $T_{w,i}$, $T_{r,o}$, $T_{r,i}$, T_b and T_s, which are interconnected with thermal resistances (convective, conductive and radiative) and capacitances (heat capacities). Other research workers (Balcomb *et al* 1977; Perry 1977) have also attempted simulation of passively heated and cooled buildings by using similar thermal network analysis. Energy conservation relations have then been derived for each of the components of the building. These equations have been solved simultaneously for the prevailing hourly ambient temperature, solar irradiation and humidity values computed from the available mean meteorological data.

2. Analysis

The heat load on a building is composed of (i) the amount of radiation that the walls absorb from out of the radiation that they receive from the sun, the sky, the ground and also that which is reflected by other objects, (ii) heat flowing into the building from the walls by conduction, (iii) infiltration of the outside air into the building and (iv) sources of heat within the building such as human or animal occupants of the building, lights, etc.

2.1. *Solar radiation*

The amount of solar radiation incident on any surface depends on its geographical location, the day of the year and the hour of the day. The solar energy incident on a horizontal surface (which can be measured) has to be related to the actual solar irradiation falling on a surface with an arbitrary orientation (Duffie & Beckman 1974). Usually, the meteorological data available list only the monthly average of the daily solar irradiation on a horizontal surface. To obtain the actual solar irradiation as a function of time on a surface of arbitrary orientation from the monthly mean, a numerical model based on the NBS–LD programme has been used (Kasuda & Ishii 1977).

2.2. *Air temperature*

The ambient air temperature influences the convective heat flux received by the walls

of the building. Here again, only the monthly average maxima and minima of temperatures are listed in the commonly available meteorological data. For obtaining the air temperature as a function of time a numerical model also based on the NBS–LD programme has been used (Hill *et al* 1975).

2.3. *Sky temperature*

The infrared downward radiation from the atmosphere is most commonly expressed in terms of a single parameter T_s which represents an equivalent temperature of the sky wherein the sky radiation is considered as that coming from a black body at the temperature. Several empirical relations have been proposed to relate T_s to T_a, the air temperature, such as (Duffie & Beckman 1974):

$$T_s = 0.0552\,(T_a)^{1.5},$$

$$T_s = T_a - 6,$$

where T is in °K. Neither of these two relations is satisfactory because the atmospheric radiation depends not only on the air temperature but also on the concentration of the infrared active gases in the atmosphere, like water vapour and carbondioxide. Several other empirical estimates for T_s have been suggested (Atwater & Ball 1978) of which the Parmelee & Aubele (1951) relation seems to give the closest agreement to measured values:

$$T_s = (0.55 + 0.33\sqrt{P_w})^{0.25}\,T_a, \tag{1}$$

where T_a is in °K and P_w is the ambient water vapour pressure in inches of mercury. This was verified experimentally as indicated in a later section. It can be noted that increasing water vapour content in the atmosphere leads to higher sky temperatures. Hence any system based on nocturnal cooling can operate effectively only when the humidity is low.

2.4. *Humidity*

The water vapour content of air controls not only the radiation from the sky, but also affects the process of evaporative cooling. If the relative humidity is high, both evaporative cooling and radiative cooling become less in magnitude. The measurement of the humidity can be accomplished by either noting the dry and wet bulb temperatures, or the relative humidity or the dew point in conjunction with the dry bulb temperature. Here again only the relative humidity measurements at one or two points in a day are commonly published in the meteorological data reports. A simple linear interpolation has been used here when data at more than one point in a day was available, but when only one reading was available, the water vapour content was taken as constant throughout the day, if the dew point was lower than the minimum temperature of the day.

2.5. *Nocturnal cooling of water*

To obtain an estimate of the extent of cooling that can result from radiative cooling at night alone, an insulated pond containing water is considered here. Such a pool of water loses heat by radiation to the sky and by evaporation. For separating the two processes, the water can be considered as enclosed within a thin transparent envelope (such as a polyethylene or PVC bag), from which no evaporation can occur. The equation for the water temperature is then

$$(\rho CAd)_p \frac{dT_p}{dt} = \epsilon_p \sigma AF (T_s^4 - T_p^4) + h_1 A (T_a - T_p), \qquad (2)$$

where the first term on the right is the radiative gain and the second term is the convective gain of heat. Here it is assumed that the water temperature is the same at the surface and everywhere within. To take care of the possibility that the average temperature is different from the radiating surface temperature, T_p, on the right hand side of equation (2) could be replaced by $(T_p - \delta)$ where δ is a small number for correcting the inequality in temperatures (Bar-Cohen & Rambach 1974).

The solution of equation (2) shows the effect of increasing the depth of the pond, while retaining the surface area of the pond (from which the radiative loss occurs) constant. Figure 2 shows the convective gain of heat and radiative losses from the pond for a 10 cm depth and also the pond temperatures for different depths of water. Table 1 lists the actual cooling due to nocturnal radiation alone.

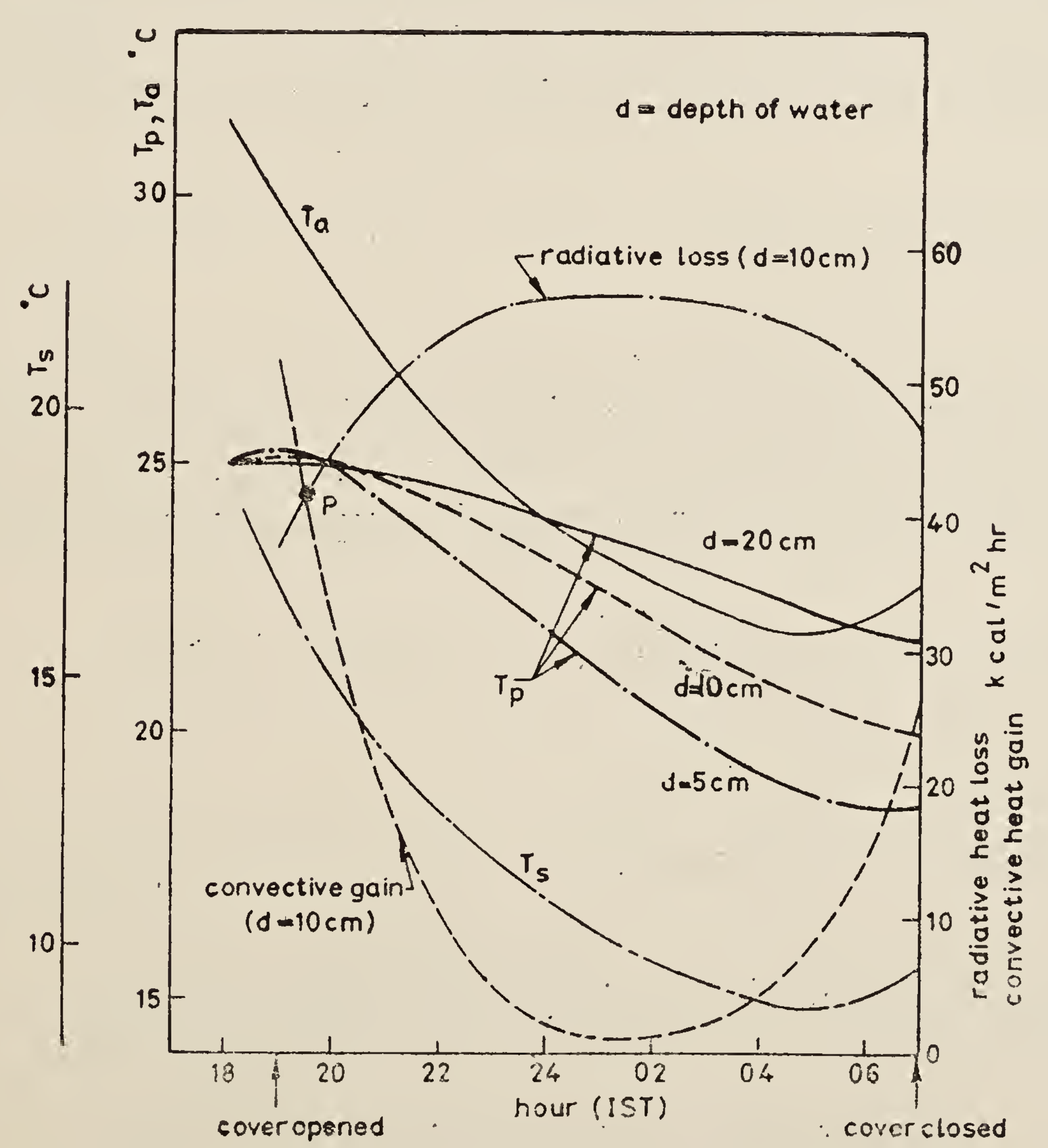

Figure 2. Temperature history of an insulated pond cooled by nocturnal radiation. (Point P indicates the optimum time for opening the cover when convective gain = radiative loss)

Table 1. Radiative cooling for an insulated pond

Depth (cm)	Heat capacity of pond (kcal/K)	Final pond temperature (°C)	Heat lost by radiation (kcal/m²)	Heat gained by convection (kcal/m²)	Total cooling for pond (kcal)
5	2,000	18·7	658·1	342·5	12,622
10	4,000	20·0	713·2	217·5	19,825
20	8,000	21·8	757·6	116·8	25,632
30	12,000	22·7	775·9	75·3	28,025
40	16,000	23·2	785·8	52·8	29,320

Initial pond temperature: 25°C
Relative humidity: 45% at 1730 hr and 90% at 0830 hr
Area of pond: 40 m²

2.6. *Evaporative cooling*

The rate of evaporation of water from a pond is estimated roughly by using Carrier's empirical relation (Hay & Yellott 1969)

$$m_E = 0{\cdot}4545\, A\, [P_{w,p} - P_{w,a}]\,(1 + 0{\cdot}24v). \tag{3}$$

However using the analogy between heat and mass transfer processes, Kuppu Rao & Radhakrishnan (1977) have derived a correlation between the Sherwood number Sh (which is the mass transfer Nusselt number) and the mass transfer Rayleigh number Ra_m as

$$\mathrm{Sh} = 0{\cdot}45\,(\mathrm{Ra}_m)^{0{\cdot}25}. \tag{4}$$

This correlation was also verified experimentally for the complete laminar natural convective evaporation regime extending beyond $\mathrm{Ra}_m = 10^6$. This correlation is however valid only for evaporation in still air. Using a relation similar to that in equation (3) to correct for air flow velocity, the evaporative cooling rate is:

$$Q_E = m_E L_E = A L_E h'_m\,(x_{w,p} - x_{w,a})\,(1 + 0{\cdot}24v). \tag{5}$$

2.7. *Thermal model for the building*

The net heat flux into the building is

$$\begin{aligned} Q_{\mathrm{in}} = {} & \sum_j \alpha_g I_{s,j}\, A_{g,j}\, S_{,j} + \sum_j U_g A_{g,j}\,(T_{g,o} - T_{g,i}) \\ & + U_w A_w\,(T_{w,o} - T_{w,i}) + U_r A_r\,(T_{r,o} - T_{r,i}) \\ & + h_i A_f\,(T_f - T_b) + Q_{\mathrm{AI}}. \end{aligned} \tag{6}$$

where the first term on the right is the solar influx through the glazed windows, the second, third and fourth terms are the conduction heat fluxes through the windows, the walls and the roof respectively, the fifth term is the heat flux from the floor and the sixth term is the air infiltration

$$Q_{AI} = \lambda V \rho_a C_a (T_a - T_b) + Q_m, \tag{7}$$

where Q_m is the heat flux associated with the flux of moisture when the water vapour content of air inside and outside is different.

The rate at which energy is deposited on the outer surface of the building is

$$\begin{aligned} Q_{\text{out}} = {} & [\alpha_w I_{s,w} A_w + \alpha_r I_{s,r} A_r] + h_o [A_w (T_a - T_{w,o}) + A_g (T_a - T_{g,o})] \\ & + \epsilon_w \sigma A_w [\tfrac{1}{2}(T_s^4 - T_{w,o}^4) + \tfrac{1}{2}(T_d^4 - T_{w,o}^4)] + \epsilon_g \sigma A_g [a(T_s^4 - T_{g,o}^4) \\ & + b(T_d^4 - T_{g,o}^4)] + h_2 A_r (T_a - T_{r,o}) + \epsilon_r \sigma A_r (T_s^4 - T_{r,o}^4). \end{aligned} \tag{8}$$

Here the first term in square brackets on the right is the sum of the solar energy falling on all the walls (note that the solar energy falling on each wall is different because of its orientation and differences in shading). The second term on the right is the convective heat term (for ease of handling the equations, all the glazed surfaces are clubbed together to have a total surface area of A_g and the same outer temperature $T_{g,o}$) and the third term is the radiative heat input term for walls and the fourth is that for windows. The fifth and sixth terms are convective and radiative input terms for the roof, that has no cover or water on it.

The energy conservation relations are derived next for all the components:

(i) For the walls.

$$Q_{\text{out},w} = Q_{\text{in},w} + (\text{rate of energy stored in the walls})$$

$$\begin{aligned} & \alpha_w I_{s,w} A_w + h_o [A_w (T_a - T_{w,o})] + \epsilon_w \sigma A_w [\tfrac{1}{2}(T_s^4 - T_{w,o}^4) + \tfrac{1}{2}(T_d^4 - T_{w,o}^4)] \\ & = U_w A_w (T_{w,o} - T_{w,i}) + C_w \frac{d[\tfrac{1}{2}(T_{w,o} + T_{w,i})]}{dt}. \end{aligned} \tag{9}$$

As is the usual practice, this equation is cast into the form for getting the hourly temperatures,

$$\begin{aligned} C_w \frac{\Delta[\tfrac{1}{2}(T_{w,o} + T_{w,i})]}{\Delta t} = {} & \alpha_w I_{s,w} A_w + h_o A_w (T_a - T_{w,o}) - U_w A_w (T_{w,o} - T_{w,i}) \\ & + \epsilon_w \sigma A_w [\tfrac{1}{2}(T_s^4 - T_{w,o}^4) + \tfrac{1}{2}(T_d^4 - T_{w,o}^4)]. \end{aligned} \tag{10}$$

(ii) The heat conducted across the walls is now equated to the heat removed from the walls convectively by the air inside the room, i.e.,

$$U_w A_w(T_{w,o} - T_{w,i}) = h_i A_w(T_{w,i} - T_b), \tag{11}$$

which yields a relation for $T_{w,i}$

$$T_{w,i} = (U_w T_{w,o} + h_i T_b)/(U_w + h_i). \tag{12}$$

(iii) For the case of uncovered roof without water on it

$$C_r \frac{\Delta[\frac{1}{2}(T_{r,i} + T_{r,o})]}{\Delta t} = a_r I_{s,r} A_r + h_r A_r(T_a - T_{r,o}) + \epsilon_r \sigma A_r(T_s^4 - T_{r,o}^4)$$

$$- U_r A_r(T_{r,o} - T_{r,i}). \tag{13}$$

and $$T_{r,i} = (U_r T_{r,o} + h_i T_b)/(U_r + h_i). \tag{14}$$

(iv) If the roof is now covered with an opaque sheet the first term becomes zero while the third term gets modified by having T_s replaced by the temperature of the cover T_c. When water is stored on the roof, which is fitted with a movable insulating cover:

$$(C_r+C_p)\frac{\Delta T_p}{\Delta t} = [a_p I_{s,r} A_r + h_2 A_r (T_a - T_p) + \epsilon_p \sigma A_r (T_s^4 - T_p^4) - m_E A_r L_E]\ X(t)$$

$$+ [h_3 A_r (T_a - T_p) + \epsilon_p' \sigma A_r (T_s^4 - T_c^4) - m_E' A_r L_E]\ [1 - X(t)]$$

$$- U_r' A_r (T_{r,o} - T_{r,i}), \tag{15}$$

where $X(t)=1$ when the cover is open and $X(t)=0$ when the cover is closed. The term in the second square bracket represents the heat gained by the water in the pond (when it is covered) through air infiltration and by radiative exchange with the cover. $T_{r,i}$ is obtained from equation (14) where U_r is replaced by

$$U_r' = [(1/U_r) + (1/h_p)]^{-1}.$$

(v) The temperature inside the building is now related by

$$C_b \frac{\Delta T_b}{\Delta T} = h_i\ [A_w (T_{w,i} - T_b) + A_r (T_{r,i} - T_b) + A_f (T_f - T_b) + A_g (T_{g,i} - T_b)]$$

$$+ Q_{\mathrm{AI}} + (1 - \tilde{\rho}_g)\ A_g I_{s,g}. \tag{16}$$

The radiative exchange terms between the walls, the roof, the floor and the glazed windows inside the building have been neglected for simplicity. But they will have to

be included if the temperature differences between $T_{w,i}$, $T_{r,i}$, T_f and $T_{g,i}$ are large. Here the building is assumed to be on the ground with a cement floor. If the building is not on the ground, another conservation relation for the floor temperature is required. Again for convenience, the floor temperature has been taken to be constant over the day and is taken equal to the mean ambient temperature.

(vi) For the windows

$$C_g \frac{\Delta[\frac{1}{2}(T_{g,i}+T_{g,o})]}{\Delta t} = h_o A_g (T_a - T_{g,o}) + \epsilon_g \sigma A_g [a(T_s^4 - T_{g,o}^4) + b(T_d^4 - T_{g,o}^4)] - U_g A_g (T_{g,o} - T_{g,i}). \tag{17}$$

The radiative contributions from the floor, the walls and the roof to the glazing have been neglected for convenience. $T_{g,i}$ is eliminated by using

$$T_{g,i} = (U_g T_{g,o} + h_i T_b)/(U_g + h_i). \tag{18}$$

Equations (10), (15), (16) and (17) together with either equation (15) or (13) are to be solved simultaneously using auxiliary relations (12), (14) and (18), for the solar irradiation I_s and T_a that are obtained as hourly values using the numerical programmes referred to earlier. The radiation terms are linearised for ease of computation (Duffie & Beckman 1974). Table 2 gives the numerical values of the heat transfer coefficients while table 3 lists the details of the buildings whose thermal performance has been simulated. The temperature T_b of the building interior depends on the value

Table 2. Convective heat transfer coefficients

Coefficients	Description	Value of the coefficients (kcal/hr m² K)
h_0	Between ambient air and outside walls	$4 \cdot 9 + 3 \cdot 3\, v$ (v=wind velocity, m/s=3·1)
h_2	Between ambient air and roof with parapet	10
h_3	Between the water surface of the pond and the cover	5
h_i	Between air and inside walls	5
h_p	Between water and roof surface	25
Radiative parameters		
a_w	Absorptivity of walls for solar radiation = a_r	0·22
ϵ_w	IR emissivity of walls	0·90
ϵ_p	IR emissivity of pond $= [(1/\epsilon_{water}) + (1/\epsilon_{transparent\ cover}) - 1]^{-1}$	0·85

Air infiltration factor: $\lambda = 1$

Table 3a. Effect of reducing the wall conductance

Thermal conductance U_w (kcal/m² hr K)	Total conductance* of walls (kcal/hr m² K)	Net conductive heat flux into building per day (kcal)	Maximum temperature °C		
			T_a	$T_{w,o}$	T_b
23	4·11	3643	33·8	36·3	33·7
10	3·33	3460	33·8	36·3	33·2
5	2·50	3348	33·8	36·4	32·7
0·5	0·45	1306	33·8	37·0	30·2

*Defined as $q_{\text{cond}} = U(T_{w,o} - T_b)$

Building dimensions: 9 m length × 4·5 m width × 3 m height (the shorter sides facing east and west)
Wall heat capacity = 2,400 kcal/K Room heat capacity = 600 kcal/K

Table 3b. Effect of increasing building heat capacity

Heat capacity C_w (kcal/K)	Net conductive heat flux per day (kcal)	Maximum temperature °C		
		T_a	$T_{w,o}$	T_b
2400	3643	33·8	36·3	33·7
3600	3892	33·8	36·1	33·5
4800	4466	33·8	36·0	33·3
7200	8208	33·8	34·9	32·7

Thermal conductance $U_w = 23$; Room heat capacity = 600 kcal/K

of the thermal capacity C_b that is taken for it. The heat capacity has been conservatively assumed to be equivalent to about 10% of that of the walls of the building excluding the heat capacity of the air inside. The heat storage in the walls of the building has been taken as $(C_w/2)\,(T_{w,o}+T_{w,i})$ in equation (10). For greater accuracy it becomes necessary to divide the wall into several nodes (Balcomb *et al* 1977) instead of treating it as a single node. The results of the computations are described in § 4.

3. Experiments

As part of an investigation on low-cost building materials, an experimental building was constructed on the campus of the Indian Institute of Science to test such building materials like stabilised mud bricks and ferro-cement roofing. Preliminary tests were conducted with this building on sky-therm airconditioning. This building was however not well suited for this purpose, because it is an L-shaped building (the south and west facing walls being 7·6m long, while the north and east facing ,wall are 4·9 m long) and has large extents of glazed windows (3·6 m² on west wall, 1·8 m² each on north and east walls) and open ventilators (1.34 m² on south and 0.54 m² on the east wall) which could not be closed. The 3·75 cm thick ferro-cement roof, on the

other hand, was well reinforced to support upto 20 cm depth of water and has proved to be adequate except for some leaks. In spite of these disadvantages, water on the roof pond (from which both radiative cooling and evaporative cooling occur) has cooled the room by about 3–4°C (besides damping out temperature fluctuations) in April which is the hottest month in Bangalore. The pond was covered by wooden boards during the day, no care being taken to prevent air infiltration into the pond. A new building is being built for carrying out passive cooling studies only.

Two other simple experiments were carried out for measuring the air infiltration rate and the sky temperature.

3.1. *Air infiltration rate*

The rate of infiltration of air depends (Sinden 1978) on windspeed and its direction, the difference in the indoor and outdoor temperatures, the openings in the building, and the fraction of the time when doors and windows are open. Usually this is determined experimentally from the rate of decrease of a tracer gas like SF_6 that is injected initially in the living area (Malik 1978). Because of the complex dependence of air infiltration rate on all these parameters, and the difficulties in modelling them only simple empirical relations relating the effects of each of the parameters on air infiltration rates are available.

Here instead of using a tracer gas like SF_6 a simple technique was evolved wherein water vapour itself was used as the tracer, since it is rather easy to measure humidity. Initially the humidity inside the room was increased by introducing steam into the room. By simultaneously monitoring the humidity inside and outside it is possible to estimate the air infiltration rate, by using the relation

$$d[x_{w,i} - x_{w,o}]/dt = -\lambda\,(x_{w,i} - x_{w,o}),$$

where x_w is the concentration of water vapour and λ the number of air exchanges per hour. This technique while not being free from interferences and errors introduced from adsorption etc., gives a rough-and-ready estimate for air infiltration rate. An average rate of $\lambda=1$ exchange per hour was measured for the experimental laboratory building even when all the doors and windows were fully closed, and winds were below 5 km/hr.

3.2. *Sky temperature measurements*

Since the radiative cooling at night depends very significantly on the sky temperature, there has to be a rational way of determining which of the several empirical relations cited earlier gives a closer estimate. For this purpose, an experiment was carried out wherein an insulated pan of water was exposed to the night sky. To prevent interference by evaporation, a transparent 2 mm glass sheet was used to cover the pan and the water was filled until it was in contact with the glass. The fall in temperature of the water in the pan was measured at regular intervals along with the wet and dry bulb temperatures of the ambient air. Equation (2) is solved using the different relations for T_s and the calculated value of the water temperature is compared with the measured value. Figure 3 shows this comparison between the measured value of

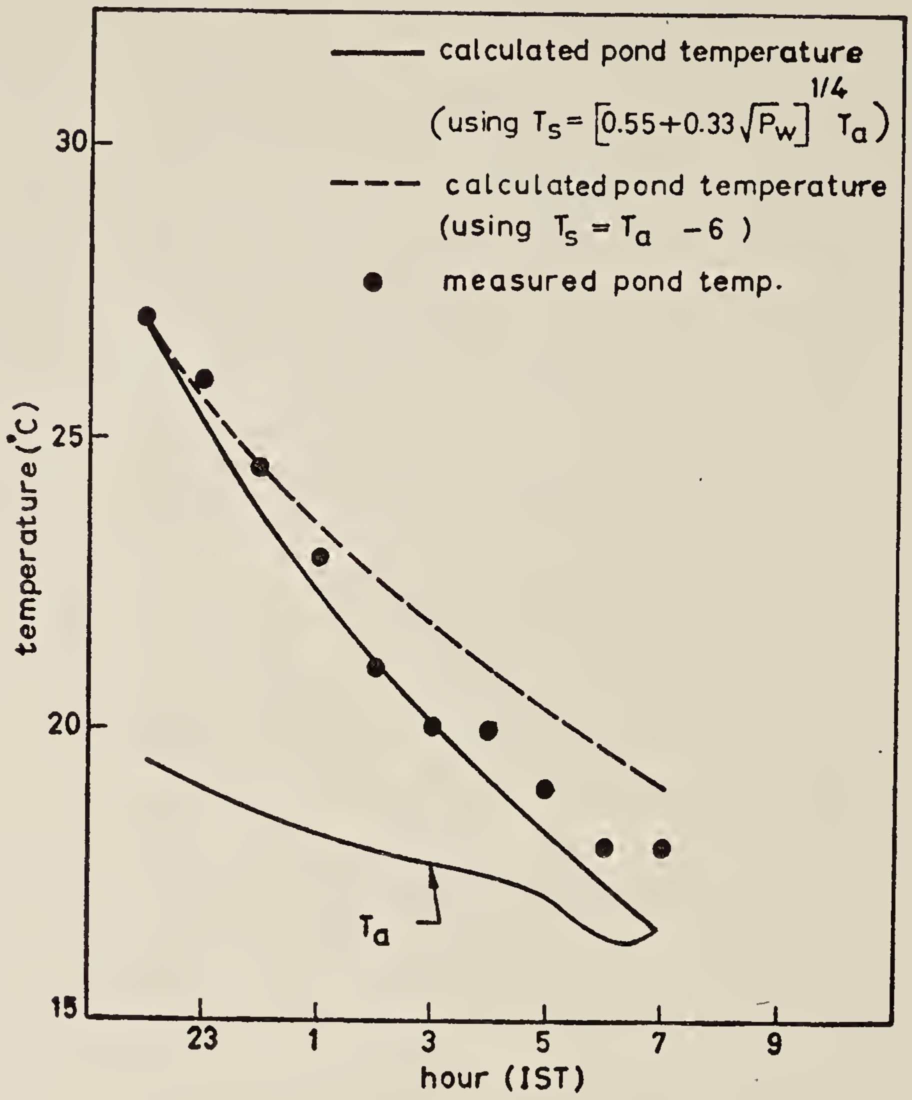

Figure 3. Experimental verification of sky temperature correlations. (14 January 1979, Bangalore)

temperature and the temperature calculated by taking two empirical relations for T_s. It was also found that the earlier relationship derived by Bliss (1961) between the emittance of clear sky ϵ_a and the dew point temperature, gave a fairly good fit, when the equation $T_s=(\epsilon_a)^{1/4}T_a$ was used. However the best fit has been obtained for the T_s relation given by equation (1).

4. Results and discussion

A large number of parameters affect the thermal behaviour of a building. To understand the roles played by these parameters the equations derived earlier were solved numerically to simulate the behaviour of some hypothetical buildings. It is seen from equation (6), the heat inflow to the building occurs by means of air infiltration and by conduction from walls besides the direct solar influx through glazed windows. The effect of wall conductance is investigated first. Figure 4 shows the variation of temperature within the building and on the outer surface of the wall for a typical day in April in Bangalore. The values of solar irradiation and ambient air temperature used here are the same as those shown in figure 6. The specifications of the building are shown in tables 3a and 3b. Table 2 lists the values of heat transfer coefficients used in the computation. The results shown were computed keeping the air infiltration and heat capacity of the walls constant. The conductance of the wall is reduced by adding low heat capacity insulation to the walls. It is seen that decreasing the conductance from 23 kcal/m^2 hr C (corresponding to 5 cm concrete walls) to 0·5 kcal/m^2 hr C reduces the temperature swing of 33·7–23·5°C to 30·1–25°C.

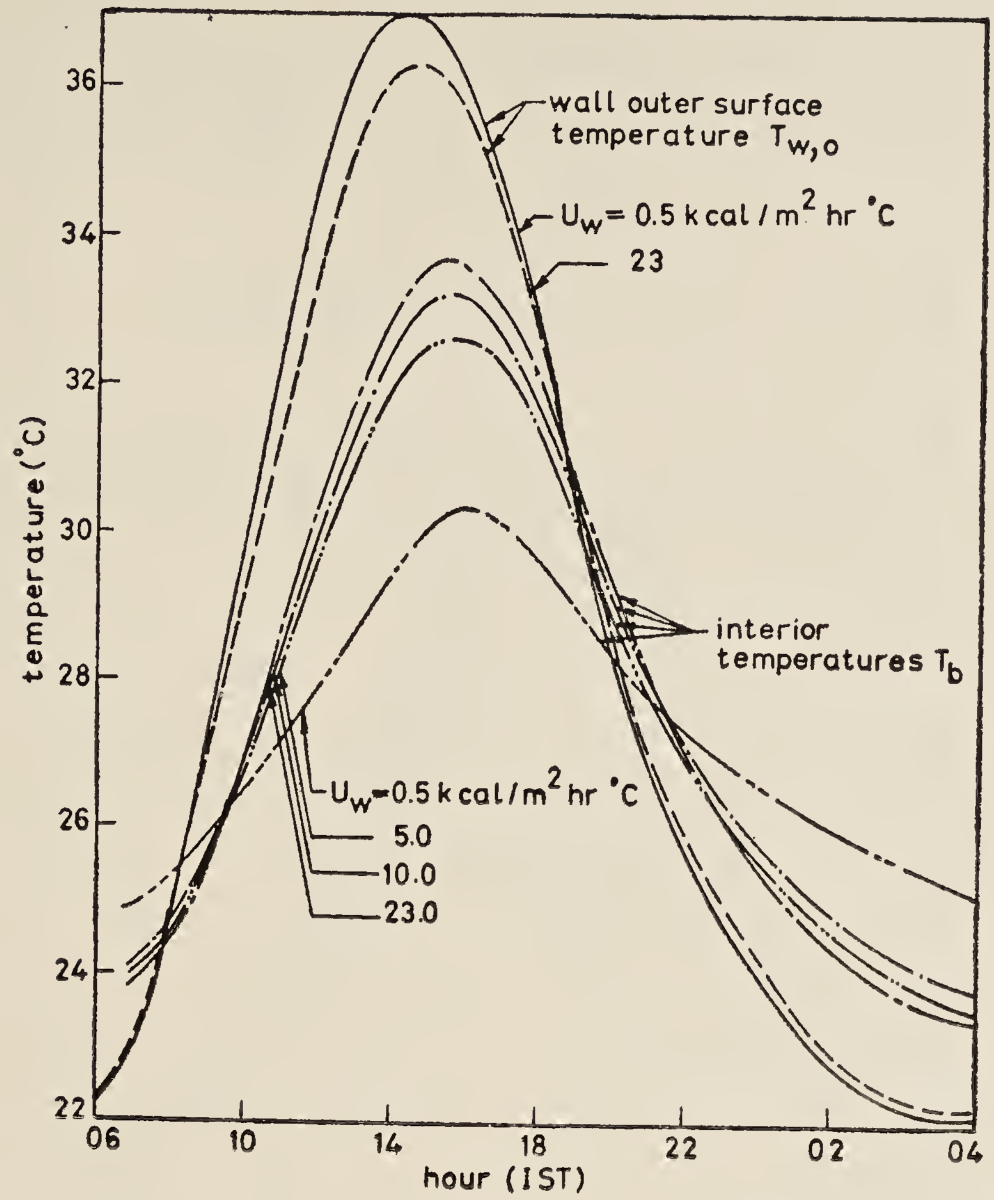

Figure 4. Effect of heat conductance U_w of the wall on $T_{w,o}$ and T_b (ambient temperature T_a and solar irradiation I_s same as that in figure 6)

The heat capacity of the walls is another parameter that affects the thermal behaviour of the building. Its effect has been investigated by changing the heat capacity, while the conductance of the wall is kept constant at the rather high value of 23 kcal/m² hr C. The results of this are shown in figure 5. The consequence of increasing the heat capacity is also to damp out the temperature swings. By enhancing the total heat capacity of the building from 2400 kcal/C to 7200 kcal/C the temperature swing of 33·7–23·5°C reduces to 32·6–24°C. Table 3 also lists the values of conduction heat flux into the room.

The solar irradiation absorbed by the walls and the roof of the building are shown in figure 6. It is seen that by far the largest component of solar heat load occurs on the roof. The effect of shading the roof alone has been investigated, the result of which is also shown in figure 6. A concrete building with 10 cm thick walls and 10 cm roof has been simulated with and without a shade such as will be provided by a movable cover over the roof. A dramatic reduction in the peak temperature inside the building occurs when the roof is shaded from the incident solar radiation.

Now the advantageous effects of large heat capacity, low thermal conductance and roof shade are all combined for a brick building which has been considered last. This building is taken to have 30 cm mud brick walls, 3·75 cm thick ferro-cement roof and a movable insulating cover over the roof which also has a water pond. The specifications of this building are listed in table 4. Figure 6 shows the temperature variation inside the building for the two cases (a) without water on the roof, but the roof shaded and (b) 10 cm depth of water enclosed in a transparent bag on the roof,

the movable insulating cover being closed from 0630 hr to 1900 hr and then opened during the night.* It is observed that with 10 cm depth of water on the roof the peak temperature during the day is 28·3°C, hardly 0·3°C higher than the prescribed value

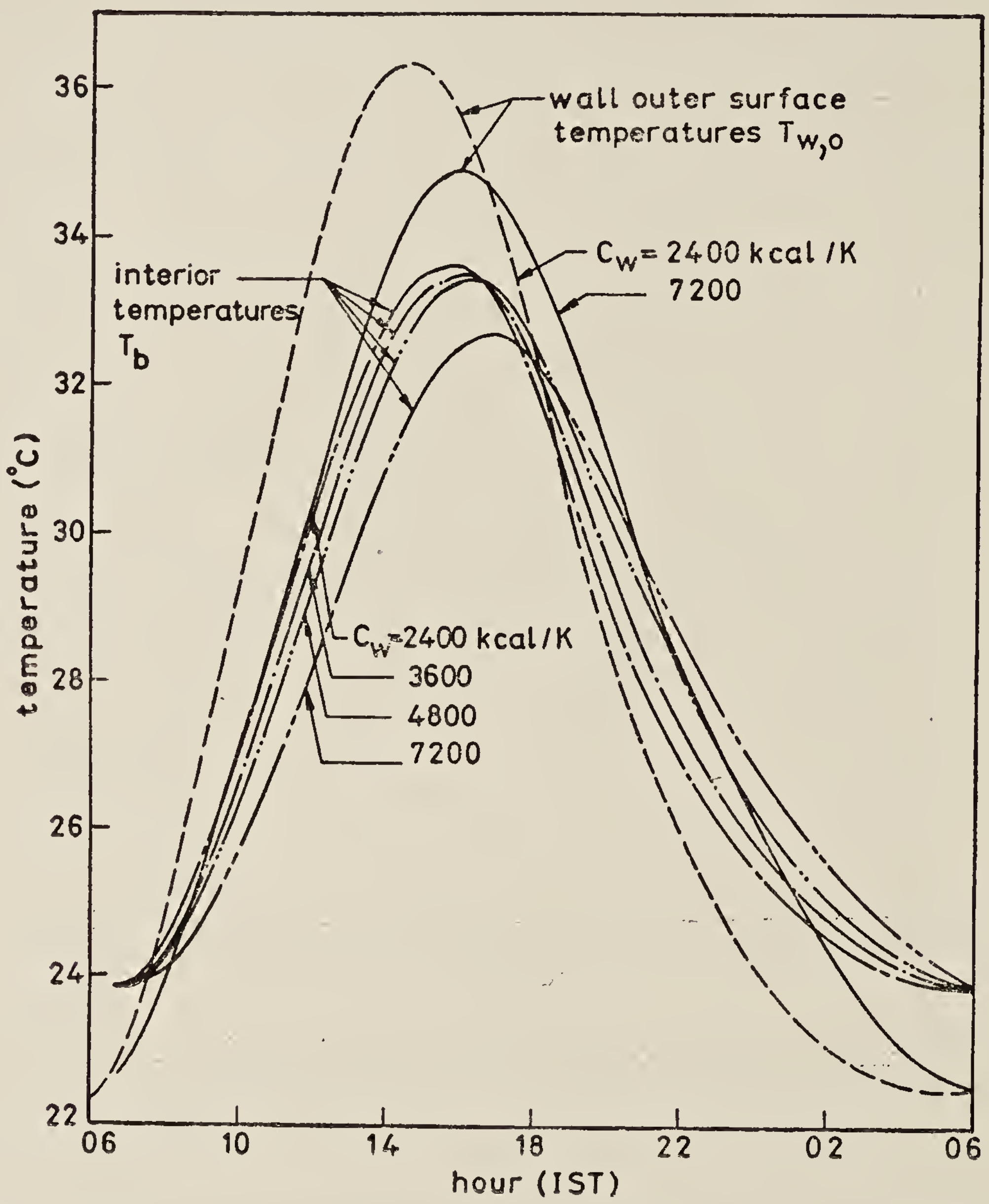

Figure 5. Effect of building heat capacity C_w on $T_{w,o}$ and T_b (ambient temperature T_a and solar irradiation I_s same as that in figure 6).

Table 4. Building parameters

		Concrete building with concrete roof	Brick building with ferro-cement roof
Wall thickness (cm)		10	30
Roof thickness (cm)		10	3·75
Conductance (kcal/hr m² K)	U_w	11·50	0·66
	U_r	11·50	32
Heat capacities (kcal/K)	C_w	3204	6624
	C_r	1602	600
	C_p	—	4050
Radiative conductance† (kcal/m² hr K)	R	4·41	4·41

†Radiative conductance R is defined as $R\,A\,(T_1 - T_2) = \epsilon\,\sigma\,A\,(T_1^4 - T_2^4)$

*The period during which the cover is to be kept open is optimum only as long as dT_p/dt is negative in equation (15) when $m_E = 0$ and the conduction term is dropped and $X(t) = 1$. This corresponds to point P in figure 2.

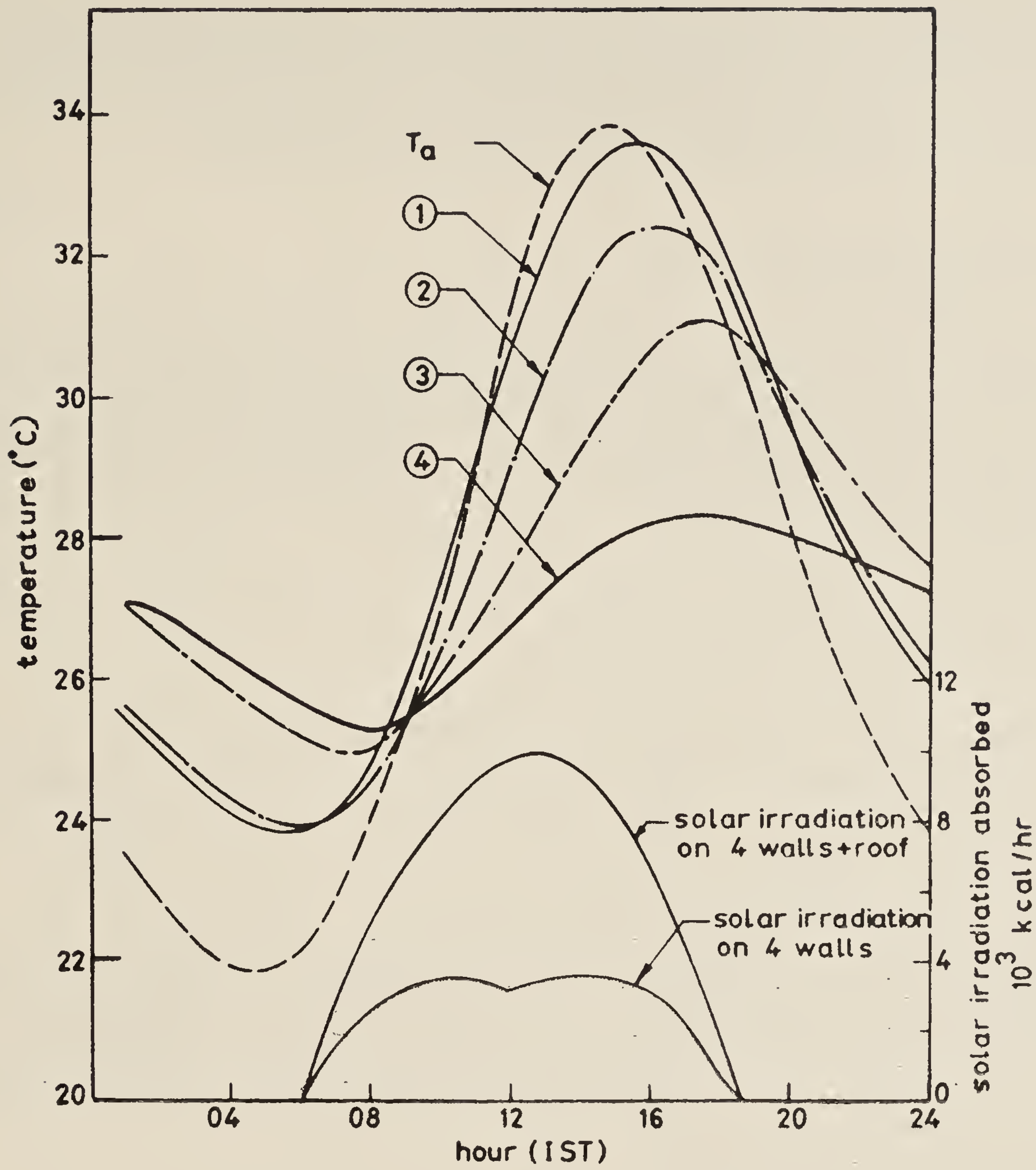

Figure 6. Temperature of the interior of the building.
1. Concrete building: 10 cm thick walls, 10 cm thick roof; 2. roof of concrete building shaded; 3. brick building: 30 cm thick mud brick walls, 3·75 cm thick ferro-cement roof (shaded); 4. Water on top of the roof of the brick building 10 cm deep, the movable insulating cover over the roof opened after 1900 hr.

of 28°C. When the depth was increased to 20 cm the peak temperature went below 28°C.

4.1 *Depth of water in the pond*

Figure 2 shows the effect of changing the depth of the pond d on T_p, the pond temperature, when only skyward nocturnal radiation is the cooling mechanism. Increasing the depth of the pond (which increases its heat capacity) leads to a higher final pond temperature. But the heat dissipated by the pond is greater as seen from table 1. This is because the radiative heat loss increases with increasing temperature difference, while the cumulative convective heat gain is reduced.

The consequences of making the pond deeper are: (a) the higher heat capacity of the pond leads to a smaller change in T_p during the heating cycle when heat is transferred from the building to the pond, i.e., T_p does not increase very rapidly during the heating cycle (b) greater heat removal capacity is available (c) but the higher values of T_p imply that the temperature difference $(T_b - T_p)$ driving heat flow into the pond is also reduced, causing a reduction in the rate of flow of heat from the

building into the pond. So the depth of the pond has to be optimised depending on the total cooling that is available and the heat removal rate that can be attained. Here the depth of the pond that appears to be optimum is 20 cm. The analysis for optimising the depth is in progress and will be presented later.

4.2 *Thermal conductance of the roof*

The effectiveness of the roof pond in either heating or cooling the building depends on the overall heat transfer coefficient between the pond and the interior of the building and the temperature difference ($T_b - T_p$). The overall heat transfer coefficient between the pond and the room is

$$U = [(1/h_p) + (1/U_r) + (1/h_i)]^{-1}.$$

By reducing the roof thickness t_r and by increasing the thermal conductivity k of the roof, the roof conductance $U_r = k/t_r$ can be enhanced. For a concrete slab of 5 cm thickness $U_r = 20$ kcal/m^2 hr C, and for ferro-cement of 3·75 cm thickness U_r is taken as 35 kcal/m^2 hr C. However the value of h_i the convective coefficient inside the room is about 5 kcal/m^2 hr C for natural convection. Then $U = 4{\cdot}38$ for the ferro-cement roof when $h_p \to \infty$. Now even if U_r is increased to 200 (for a 2 mm thick steel plate) U increases to 4·87 an increase of 10% only. On the other hand, a significant increase in U can result only if h_i is increased by forced circulation of air (by a ceiling fan for example) or by using a fan for circulating air over a heat exchange coil carrying water from the pond.

The total solar irradiation absorbed per day by the walls and roof is about 31,500 kcals. This is a high estimate because no shade is assumed and the absorptivity of the walls is taken to be 0·22 (whereas it can be as low as 0·16 for whitewashed walls). The heat dissipated by radiation from the roof is about 25,630 kcals for the 20 cm deep pond. In the simulation presented here no evaporative cooling has been considered. Evaporative cooling may also be utilised if additional cooling is required, as it may be in other locations. At 1730 hr when the relative humidity is 45%, the evaporative cooling is about 4200 kcal/hr from the pond surface.

As to the actual storage of water over the roof it is preferable to seal the water inside transparent bags to prevent evaporative cooling (which is undesirable during certain parts of the year) and spray water over the roof only when evaporative cooling is necessary. This has been conventionally accomplished by the use of PVC bags containing water which are UV-inhibited to provide a reasonably long life. A glass cover could however be used by filling the water until it touches the glass sheet. The ferro-cement roof experimented with here is reasonably waterproof but if the roof is exposed to the sun without water in the pond, cracks develop in it which lead to leaks. So it is desirable to use a water-proofing coat like asphalt and always keep water on the roof. By keeping the water covered by a transparent sheet the problem of the water pool acting as a centre for breeding mosquitos can also be avoided. The movable insulating covers that are required could be made of several layers of bamboo matting impregnated with a filler to cover up the pores. One such cover was used here for trial purposes and appears to be promising. The contribution from the air infiltration (which was taken to be equal to one exchange per hour)

was not found to be very important in this case because the differences in temperature between inside the building and ambient air are not very large.

5. Conclusions

A thermal model for predicting the thermal behaviour of a passively cooled building has been developed here. This model has been used to simulate the performance of a building which is being planned to be constructed for use as a storage room for cocoons and for rearing silk worms. The use of massive building walls which at the same time, have low thermal conductance helps to damp out the temperature swings. Nocturnal cooling by radiation alone can offset almost all the heat gained by the building through absorption of solar irradiation, conduction through the walls and air infiltration. In some cases however evaporative cooling may also be required in addition. So water stored in transparent sealed containers (with water sprayed over it if necessary for additional evaporative cooling) on the roof along with movable insulating covers will be sufficient to control the temperature within the limits specified, in regions where the humidity is low or moderate.

This work was originally started at the initiative of Professor K Krishna Prasad and Professor A K N Reddy. The authors wish to acknowledge the help of Mr N S Birdie who conducted some of the experiments cited here and Major P Radhakrishnan who also carried out some experiments and analysis.

List of symbols

A	area (m^2)
a, b	view factors for the window to sky and ground respectively
C	heat capacity (kcal/K)
c	specific heat (kcal/kg K)
D	diffusion coefficient (m^2/hr)
d	depth of water in pond (m)
F	view factor for the pond to sky
h	heat transfer coefficients (kcal/hr m^2 K)
h'_m	mass transfer coefficients (m/hr)
I_S	solar influx (kcal/hr m^2)
l	characteristic dimension (m)
L_E	latent heat of vaporisation (kcal/kg)
m_E	mass flux due to evaporation (kg/hr m^2)
$P_{w,p}$ $P_{w,a}$	partial pressure of water at the temperature of pond (T_p) and air (T_a) respectively, $''H_g$
Q	heat flux (kcal/hr)
Ra_m	mass transfer Rayleigh number $[g\beta\,(\tilde{x}_{w,p} - \tilde{x}_{w,a})\, l^3/\nu D]$
S	shading factor
Sh	Sherwood number ($h'_m\, l/D$)
T	temperature (K)

U	conductance (kcal/hr m^2 K)
V	volume of the building (m^3)
v	velocity of air (m/s)
x_w	mass concentration of water vapour (kg/m^3)
$\tilde{x}_w$	mass fraction of water vapour
α	absorbitivity
β	expansion coefficient
ϵ	emissivity
ϵ_e	equivalent emissivity $= (1/\epsilon_1 + 1/\epsilon_2 - 1)^{-1}$
ϵ_1, ϵ_2	emissivity of surfaces 1 and 2 which are parallel
λ	air infiltration factor
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($4{\cdot}89 \times 10^{-8}$ kcal/hr m^2 K^4)
ν	kinematic viscosity (m^2/s)
$\tilde{\rho}$	reflectivity of window glazing

Subscripts

a	ambient air
AI	air infiltration
b	room
c	insulating cover
d	ground
f	floor
g	glass
i	inside
m	moisture
o	outside
p	pond
r	roof
s	sky
w	walls

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Studies in biogas technology. Part I. Performance of a conventional biogas plant

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Abstract. This paper gives an account of a conventional 5·66 m^3/day (200 cubic ft/day) biogas plant which has been instrumented, operated and monitored for $2\frac{1}{2}$ years. The observations regarding input to the plant, sludge and biogas outputs, and conditions inside the digester, have been described. Three salient features stand out. First, the observed average daily gas yield is much less than the rated capacity of the plant. Secondly, the plants show ease of operation and a very slow response to reductions and cessations of dung supply. Thirdly, the unexpectedly marked uniformity of density and temperature inside the digester indicates the almost complete absence of the stratification which is widely believed to take place; hence, biogas plants may be treated as isothermal, ' uniform ' density, most probably imperfectly mixed, fed-batch reactors operating at the mean ambient temperature and the density of water.

Keywords. Cattle wastes; biogas plant; anaerobic digestion; manure; sludge; yield; gas production; material balance; nitrogen; pH; temperature; density; plant-scale studies; stratification; reactor; steady-state reactor; batch reactor; constant flow reactor; completely mixed reactor; stability; solids; total solids; volatile solids.

1. Introduction

The potential of biogas plants, as a source of both energy and fertiliser, was first publicised by the Khadi and Village Industries Commission (KVIC) and then clearly revealed in the techno-economic review of Prasad *et al* (1974). This study, along with others on the same subject (Mahkijani & Poole 1975; Reddy & Krishna Prasad 1977), showed that biogas plants could play a major role in overcoming the long-standing ' energy crisis ' in rural areas. At the same time, many state-of-the-art reviews highlighted several important lacunae in the knowledge-base of this promising technology (Kirsch & Sykes 1971; Meynell 1976; Pyle 1978; Prasad *et al* 1974).

A programme of work was therefore initiated with four objectives: (i) to obtain reliable information on the behaviour and performance of conventional biogas plants of the KVIC design; (ii) to develop a theory for the optimisation of the dimensions of biogas plants; (iii) to understand the heat transfer processes in these plants and (iv) to develop a simple, inexpensive technique for heating biogas digesters.

The progress achieved with respect to these four objectives is described in this paper, each part of which focusses on one of the objectives. This first part deals with the conventional plant of KVIC design that was set up at the Institute the measurements that were made, and the performance that was observed.

2. Description of experimental biogas plant

The experimental biogas plant consists of two parts: (i) the biogas plant proper and (ii) an instrumentation pit.

The biogas plant is of a KVIC design for a daily output of 200 cubic ft (5·66 m^3) of biogas.* The masonry digester is 1·98 m in diameter and 4·88 m deep. A partition wall separates this cylindrical digester pit into two halves. The gas holder consists of an inverted 'drum', 1·83 m wide and 1·22 m high, made of 12 gauge (0·27 cm) thick mild steel. The gas holder floats up and down on a central guide frame fixed to the partition wall. In addition, the plant has an above-ground inlet tank for charging slurry, and a below-ground outlet tank for receiving the processed sludge. These features of the biogas plant are shown in figure 1.

A pit of the same dimensions as the digester, and adjoining it, has been provided to accommodate the instrumentation for studies on temperature, density and pH distribution inside the digester. In particular, the instrumentation pit permits access to the digester via portholes through which samples can be withdrawn and thermocouples can be inserted. For locating the thermocouples at desired places in the digester, an aluminium framework is rigidly fixed to the concrete bed of the digester. GI pipes of 19 mm diameter have been embedded in the digester wall at intervals of 30·5 cm to permit the slurry to be withdrawn for analysis and for density and pH measurements. The 7·6 cm diameter pipes going through the digester wall at two positions are connected to a centrifugal pump which can be used for draining the slurry. These details are shown in figure 2.

3. Observations

The instrumented biogas plant has been in operation for about 2½ years since December 1976 when charging with cattle dung was commenced. The regular operation consists of the following activities:

(i) weekly analysis** of the dung for total volatile solids,

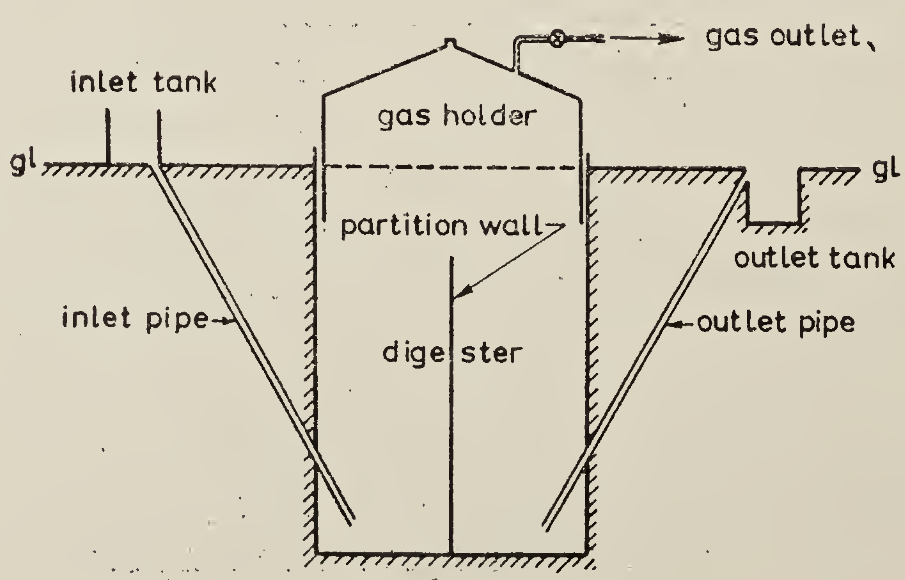

Figure 1. Biogas plant

*Unfortunately, the operating temperature corresponding to the rated capacity is not stated, but presumably it is 25°C.

**Initially, the analysis was carried out daily.

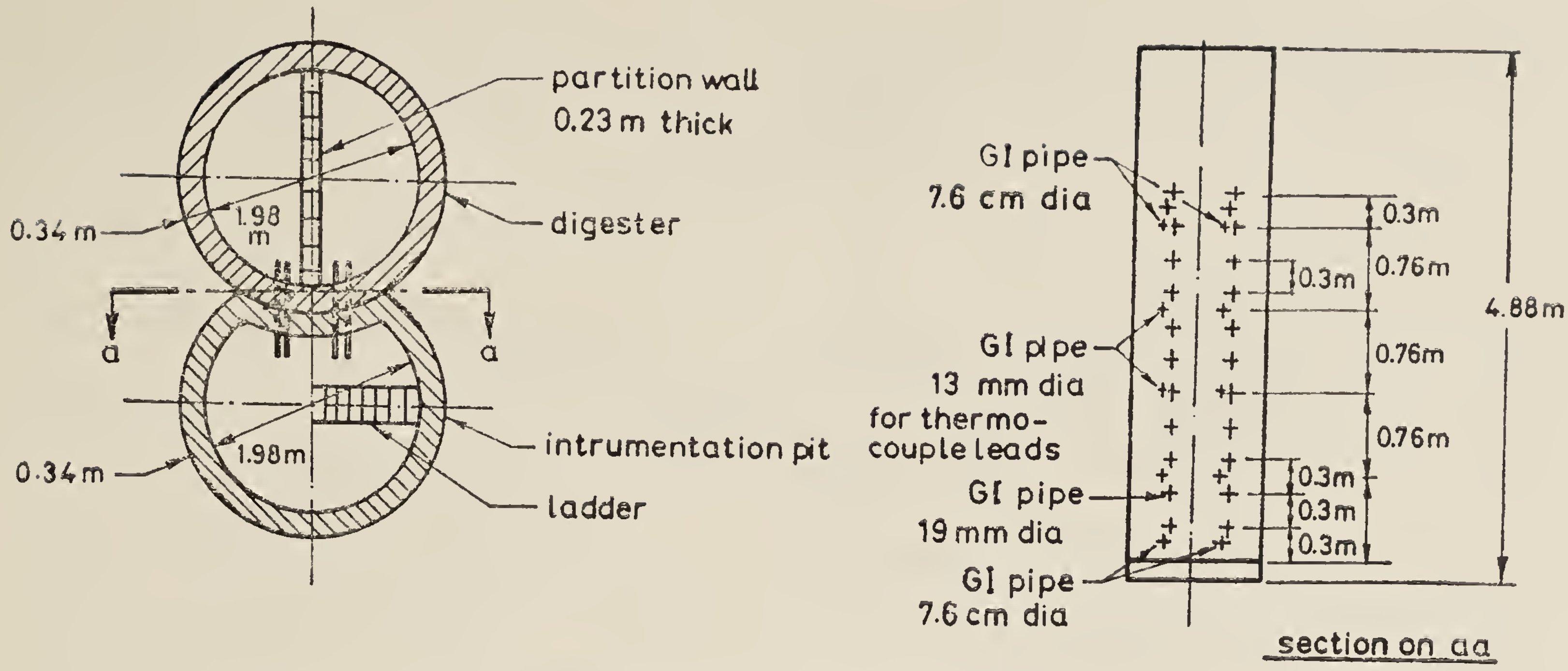

Figure 2. Details of digester and instrumentation pit

(ii) daily charging the plant with fresh dung (less than one-day old) made into a 1 : 1 (by weight) mixture with water,

(iii) daily measurement of the gas yield over 24 hr periods,

(iv) daily measurement of the weight of slurry displaced by the charging of slurry.

In addition, the following measurements were made for specific periods.**

(i) daily estimation of carbon and nitrogen in the influent and effluent for about a month,

(ii) daily estimation of the CO_2 percentage in biogas for the initial six months, and of the H_2S content for about a month,

(iii) daily measurement of the temperature at 32 locations, and density and pH at 18 locations each, inside the digester for about six months.

The information obtained from these measurements will now be described in detail, the particular values reported below being averaged over a six-month period of observation from January to June 1977.

3.1. *Input to biogas plant*

The analysis of the cattle dung which was supplied to the biogas plant by a local vendor is shown in figure 3.

It is known (Meynell 1976) that the optimum solids content for anaerobic fermentation is 8–10% which is the basis for diluting the cattle dung, which has a total solid content of 17% in an approximately 1 : 1 ratio.

The optimum carbon/nitrogen (C/N) ratio has been reported to be 25 (Meynell 1976) in contrast to the value of 16 in the present experiments, but no attempt was made to alter the C/N ratio in the input by means of additions (e.g. straw) because it was a deliberate objective in this study to observe the plant performance with an input of cattle dung only.**

*The measurements were restricted to limited periods because constant trends were observed, which made further measurements unnecessary.

**Most of the 60,000 biogas plants in the country operate solely with cattle dung.

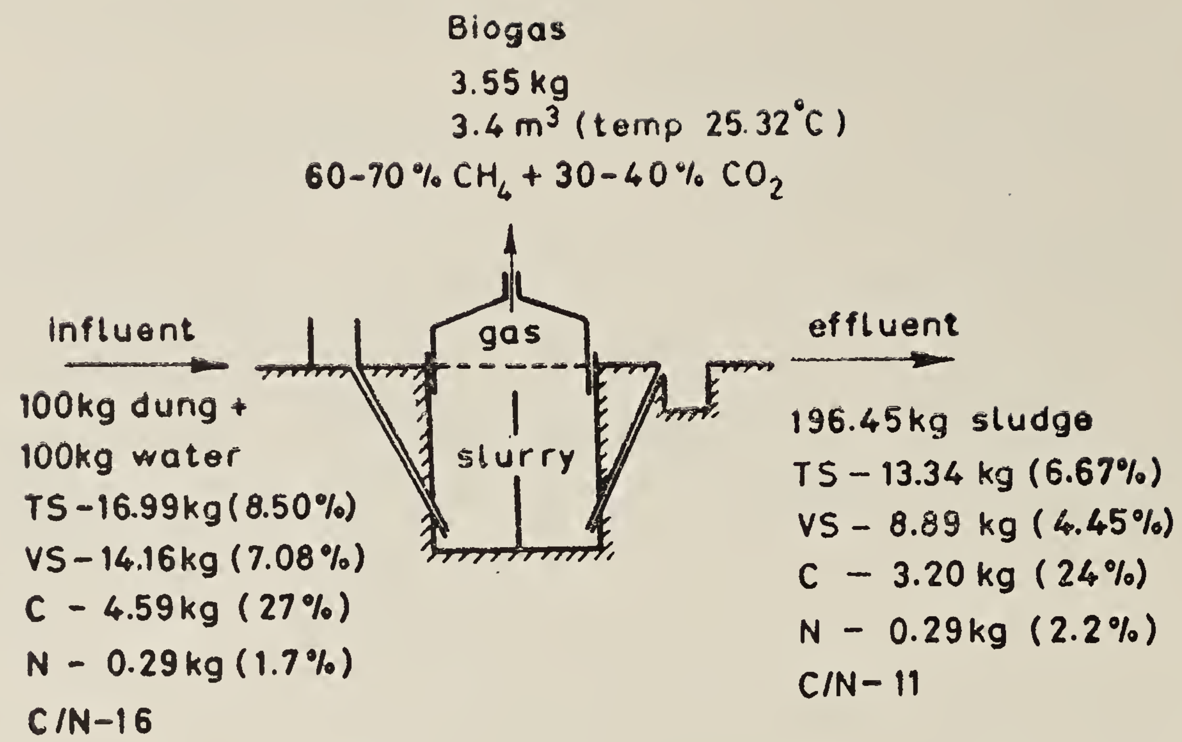

Figure 3. Mass balance of a biogas plant

Over the six-month period during which the mass balance was worked out (see figure 3), the cattle dung was charged into the plant at the rate of 122 ± 5 kg fresh dung per day.

3.2. *Sludge output*

The fresh sludge, which is the effluent from the plant, yielded the analysis shown in figure 3. It can be seen that there was a reduction of 21·4% and 37·14% in total solids and volatile solids respectively. These observed values are in reasonable agreement with the literature values of 33% and 36% respectively (Jewell *et al* 1976).

The nitrogen percentage which was taken on a dry weight basis in the *fresh* sludge i.e., 2·2% was more than that in the input, viz., 1·7%, but this increase can be simply explained by the reduction in total solids.

The effect of storing fresh sludge and cattle dung in the open air was also studied (Rajabapaiah 1979). On keeping, the nitrogen content of cattle dung fell from an initial value of 1·7% to a final value of 0·9% in about 10 days after which it remains constant. In contrast, the corresponding value for sludge effluent decreased from 2·2%, to a constant 1·9% in about 3 days. Thus, sludge dried for more than about 3 days had a nitrogen content which was 2·1 times the value for cattle dung stored (for manurial purposes) in the open for more than about 10 days.

3.3. *Biogas output*

The average yield of biogas over the six-month period of observation was 4·15 m³/day (146·5 cubic ft/day) and the gas composition was about 60% CH_4 and 40% CO_2. H_2S was observed to the extent of 0 06%. During this period, the mean ambient temperature was 25·32°C.

The average biogas yield per unit input of cattle dung was 0·034 m³/kg wet dung corresponding to 0·200 m³/kg dry dung or total solids. The yield can also be expressed as 0·24 m³/kg volatile solids. These values compare well with the yields reported by the KVIC (Anon 1974).

It must be noted, however, that the actual biogas yield from the plant was 27%

less than its rated value of 5·66 m^3/day. Even when the charging rate was stepped up to 150 kg fresh dung/day, the biogas yield was 24% of this rated value.

3.4. *Conditions inside the digester*

The slurry density was approximately within 3% of the density of water at all the 18 points inside the digester where daily measurements were made for about 5 months. Incidentally, the slurry density was between the density of influent (1·03 g/cc) and that of the effluent (0.97 g/cc). Thus, there was hardly any stratification of density inside the digester.

The slurry pH was 6·90 throughout the digester, though the influent pH was 7·01.

The temperature at all the 32 points where it was measured, i.e., at 4 planes (1·5, 2·3, 3 and 3·8 m depths) and 8 locations on each plane, was constant to within 1°C, and virtually identical to the mean ambient temperature. As in the case of density, the temperature also was virtually uniform inside the digester.

3.5. *Long term performance*

After about 1½ years of operation, considerable difficulty was experienced in pushing in the daily charge and in withdrawing slurry samples through the lowest porthole on the inlet side. When the porthole was opened, it was found that coarse sand, obviously from the input dung, had built up at the bottom of the digester to a height of at least 0·3 m. This observation not only reveals an important operational problem, but also underlines the need to charge sand-free dung or to have some sand-removing precaution.

Another interesting observation arose from an unforeseen reduction in dung supply, during which the average biogas yield fell to 2·11 m^3/day, followed by a total stoppage of dung supply for a period of 18 days. The following response of the biogas plant was observed: the gas yield dropped gradually over this period from the value of 2·11 m^3/day to 0·97 m^3/day. Further, when regular charging was resumed, the gas yield slowly built up to the normal value. This result is an indication of the slow response of biogas plants to fluctuations in dung inputs.

4. Discussion

On the basis of these studies, certain conclusions can be drawn:

(i) Over the long period of observation, the conventional biogas plant has consistently yielded at 25-32°C about 25% less gas than its rated capacity of 5·66 m^3/day,* though the gas yield per unit weight of cattle dung (0·200 m^3/kg total solids) is not lower than what is reported by the designers of the plant. The shortfall in gas yield appears to have little to do with the daily charging rate—even when the latter was increased by 22%, the shortfall only decreased by 3%. Thus, the capacity of the conventional plant for cattle-dung inputs appears to be overrated.

(ii) The observations testify to the ability of the plant to withstand reduction and

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*Assuming that this rating is for a temperature of about 25°C.

cessation in dung supply. In addition, the plant is exceedingly easy to operate, and has thus far offered virtually no maintenance problems (the gas holder has been painted only once in the $2\frac{1}{2}$ years and shows little corrosion). These factors of stability of performance and ease of operation supplement the already powerful arguments for an intensification in the use of biogas energy.

(iii) The sustained observation over a period of about 6 months of markedly uniform conditions of density and temperature in the digester imply that, inside the reactor, there is hardly any stratification worth mentioning. The almost complete uniformity of density and temperature inside the biogas plant is an unexpected result, for it is generally believed that there is a significant extent of stratification. In fact, it is this belief which has influenced the dimensioning of biogas plants, which is a matter discussed in the next part of the paper.

(iv) Conventional biogas plants are fed daily—thus, they are not ideal batch reactors. However, the feeding of input is only for about 30 min, whereas all data are averaged over at least 24 hr; hence, for about 98% of its life, a biogas plant experiences a batch operation.

The daily charging of input into conventional biogas plants leads to the daily displacement of sludge—thus, flow conditions exist only for this brief period, i.e., these plants are not constant flow reactors.

In view of the daily loading, and the resulting perturbations inside the digester, conventional plants are not in a perfect steady-state.

There is a decrease in total solid content from a value of about 8·5% in the input to about 6·8% in the displaced sludge. This change in input and output compositions is associated with a 6% decrease in density, from an influent density which is 3% higher than the density of water to an effluent density which is 3% lower than that of water. Hence, the density throughout the digester is within 3% of the value of that of water, i.e., it is almost uniform. The temperature inside the digester is maintained by the heat transfer processes (cf. part III of this paper) at values which are within 1°C of the mean ambient temperature. The production of biogas from an 'infinite' number of uniformly and randomly distributed sources facilitates this homogeneous temperature distribution. Notwithstanding the isothermal and virtually uniform density conditions inside the digester, it may not be correct to describe a conventional biogas plant as an ideal mixed reactor because the concentration of total/volatile solids is almost certain to vary between the entry and exit regions of the digesters.

In conclusion, therefore, conventional biogas plants are neither ideal batch nor constant flow reactors. Also, they are not in perfect steady-state, and they are most probably not completely mixed. A more rigorous characterisation requires further investigation of transient behaviour, diffusive transport, spatial variations of the concentrations of total/volatile solids, generated acids, bacteria, etc. Tentatively, a conventional biogas plant may be viewed as an isothermal, 'uniform' density, most probably imperfectly mixed, fed-batch reactor operating at the mean ambient temperature and the density of water.

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Centre) and Professor R Kumar (Indian Institute of Science) for their valuable comments on the characterisation of the biogas reactor. They would also like to express their special gratitude to Professor M V Narasimhan who was responsible for the overall co-ordination of the project and generously shouldered all the onerous administrative burdens. This work has been funded by the Tata Energy Research Institute to whom the authors are indebted for invaluable support.

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Studies in biogas technology. Part II. Optimisation of plant dimensions

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Abstract. In this paper, the design basis of the conventional Khadi and Village Industries Commission biogas plants has been elucidated. It has been shown that minimisation of the cost of the gas holder alone leads to the narrow and deep digesters of conventional plants. If instead, the total capital cost of the gas holder plus digester is minimised, the optimisation leads to wide and shallow digesters, which are less expensive. To test this alternative, two prototype plants have been designed, constructed and operated. These plants are not only 25–40% cheaper, but their performance is actually slightly better than the conventional plants.

Keywords. Biogas plants; dimensions; design; optimisation; modifications; gas production; yield; capital costs; economies of scale.

1. Introduction

One of the first 'surprises' confronting newcomers to the field of biogas technology is the absence of a theoretical approach to the detailed dimensioning of biogas plants. There is, of course, the trivial calculation of the volume V' of the digester viz.,

$$V' = v_{sl}\, t_d, \tag{1}$$

where v_{sl} is the volume of slurry with which the plant is charged daily, and t_d is the detention time of the slurry in the plant. But little has been said about the diameter and height of the gas holder (in floating cover-cum-gas-holder type of plants) and of the digester.

In practice, however, a wide variety of plants have been described—from shallow and long horizontal digesters to narrow and deep vertical plants. The well-known design propagated by the Khadi and Village Industries Commission (KVIC) is of the latter type. For instance, the conventional biogas plant with a rated capacity of 200 cubic ft biogas per day (5·66 m^3/day), which has been studied in the programme of work described in this paper (cf. part I) has the following dimensions: diameter and height of gas holder—6 ft (1·83 m) and 4 ft (1·22 m) respectively; and diameter and depth of digester—6½ ft (1·98 m) and 16 ft (4·88 m) respectively. Enquiries

regarding why conventional digesters are made so deep bring forth informal arguments regarding the density stratification inside digesters, the need to bury them deep in the ground in order to insulate them from the ambient temperature, etc. Since such answers are inconsistent with the findings of this study (cf. part I of this paper), and since the dimensions of biogas plants are a major factor in capital costs, it was considered essential, firstly, to understand the basis, if any, underlying the dimensions of conventional plants, and secondly, to develop a rationale for optimising the dimensions of biogas plants. The results of these efforts are described below.

2. Optimisation based on minimising gas holder cost

In the conventional plants of KVIC design, the mild steel (floating) gas holder accounts for a substantial percentage (about 40%) of the total cost of the biogas plant. If R, R_s and R_r are the capital costs of the gas holder, its sides and its roof respectively

$$R = R_s + R_r,$$

$$= \pi D h t \rho u + (\pi D^2/4) t \rho u, \qquad (2)$$

where D is the diameter of the gas holder, h its height, t its thickness, ρ its density and u, its unit cost in Rs/kg (taking into account the cost of steel, transport, fabrication, welding and painting). Further, the height h of the gas holder is given by

$$h = 4V/\pi D^2 = 4\gamma C/\pi D^2, \qquad (3)$$

where V is the volume of the gas holder and γ is the maximum fraction of the daily gas production, i.e., actual plant capacity C, which is intended to be stored in the gas holder. Combining (2) and (3), the result is

$$R = (4\alpha\gamma C/D) + (\pi\alpha D^2/4), \qquad (4)$$

where $\alpha = t\rho u. \qquad (5)$

If R is considered to be the objective function which is sought to be minimised, i.e., if R is differentiated with respect to D and the result is set equal to zero, the diameter D_K corresponding to this minimum-cost gas holder is

$$D_K = (8\gamma/\pi)^{1/3}\, C^{1/3}, \qquad (6)$$

i.e., D_K increases linearly with $C^{1/3}$, the slope being given by $(8\gamma/\pi)^{1/3}$. Further, the height of such a gas-holder is

$$h_K = 4V_K/\pi D_K^2 = 4\gamma C/\pi D_K^2, \qquad (7)$$

and its cost is given by

$$R = (3a\pi^{1/3}\,\gamma^{2/3})\,C^{2/3}, \tag{8}$$

as may be shown by combining equations (4) and (6).

It is interesting that if γ is required, as it is in the conventional Indian plants, to have a value of 60% of the rated daily gas production (corresponding to a gas storage of 12 hr overnight gas production plus an excess storage capacity of 20% of this 12 hr production), it turns out (figure 1) that the least-square line drawn through the D vs $C^{1/3}$ plots for the conventional Indian plants coincides with the plot of equation (6) for $\gamma = 0{\cdot}6$. Evidently, the diameters of the gas holders of these plants have been chosen so as to minimise the costs of the gas holders.

Further, the design of the conventional plants is such that the diameter of the digester pit is equal* to that of the gas holder plus about 6 in. (~15 cm) to facilitate free up and down floating of the gas holder as it fills with gas and empties. That is, for design purposes, it can be assumed to be within about 10% that $D'_K = D_K$ where D'_K is the diameter of the digester pit**.

In such a design, the depth h'_K of the digester pit becomes

$$h'_K = 4V'/\pi D'^2_K = 4V'/\pi D^2_K. \tag{9}$$

But from equation (1),

$$V' = (m_{sl}/\rho_{sl})\,t_d, \tag{10}$$

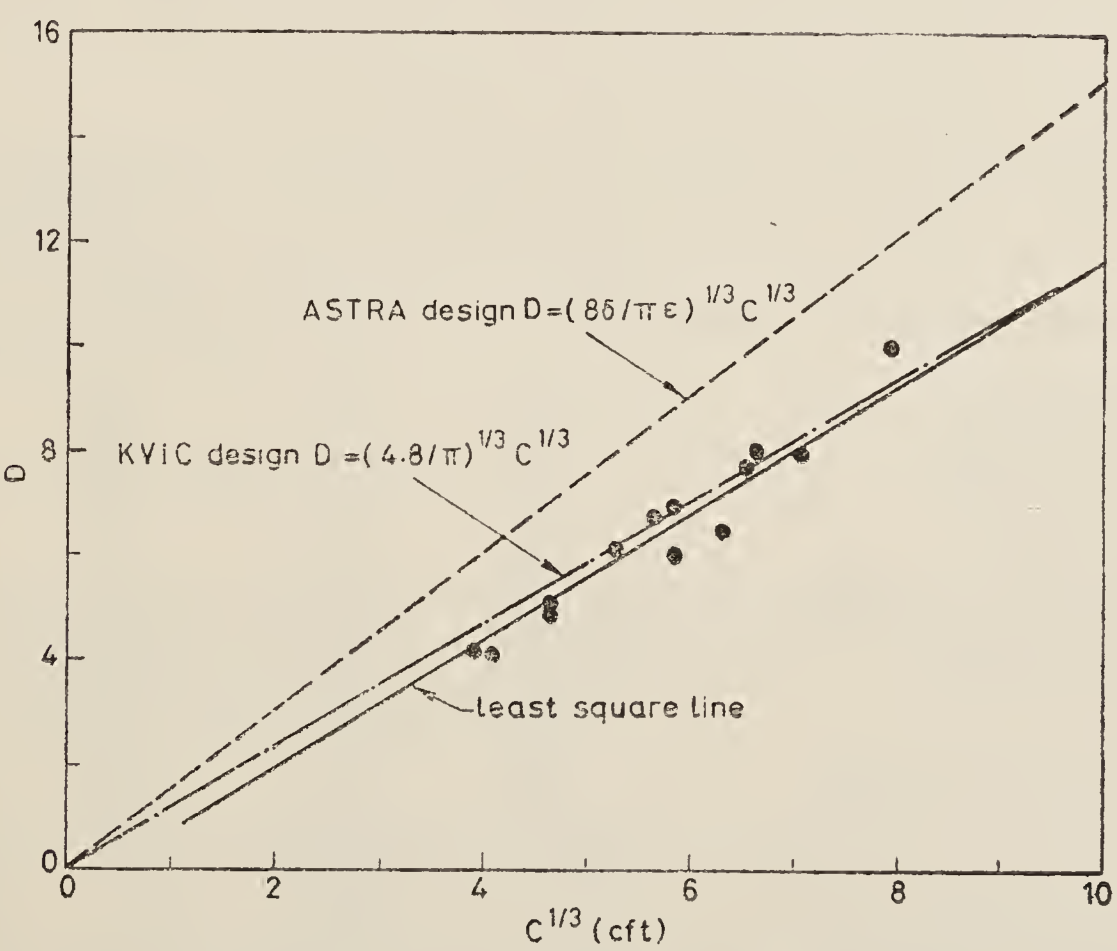

Figure 1. Variation of diameter with cube root of capacity

*This is to ensure the anaerobic seal for the fermentation process.

**Throughout the rest of part II of this paper, primed dimensions refer to the digester and unprimed ones to the gas holder.

where ρ_{sl} and m_{sl} are the density of the slurry and the mass of the slurry which is charged daily. Or, since $m_{sl}=2m_{WD}$ because of the 1 : 1 (by weight) mixture of m_{WD} and m_W, the masses of wet dung and water charged daily, and $m_{WD}=C/Y$ where C and Y are the daily gas yield of the biogas plant and its gas yield per unit weight of wet dung respectively,

$$V' = 2Ct_d/\rho_{sl}\, Y = 2\,\phi\, C, \tag{11}$$

where $$\phi = t_d/\rho_{sl}\, Y. \tag{12}$$

Hence $$h'_K = 8\,\phi\, C/\pi\, D_K^2, \tag{13}$$

and $$h'_K/D'_K = \phi/\gamma. \tag{14}$$

Conventional biogas plants are designed on the basis of $t_d = 52$ days, $\gamma = 0{\cdot}6$, $\rho_{sl} \approx \rho_{water} \approx 1$ g/cm³ and $Y = 34$ cm³ biogas/g wet dung (≈ 3 cubic ft biogas/lb total solids), and therefore since $\phi = 1{\cdot}53$,

$$h'_K/D'_K \approx 2{\cdot}5, \tag{15}$$

which implies *narrow and deep digester pits.*

For example, according to this approach to the design of conventional plants, a 200 cubic ft/day plant requires, according to equations (6), (7) and (13), a gas holder diameter and height of about 6·5 ft (2 m) and 3·5 ft (1 m) respectively and a

Table 1. Comparison of conventional and modified plants

	200 cubic ft/day (5·66 m³/day) plants		60 cubic ft/day (1·70 m³/day) plants	
	KVIC	ASTRA	KVIC	ASTRA
Gas holder diameter (m)	1·83	2·44	1·35	1·68
Gas holder height (m)	1·22	0·61	0·76	0·46
Gas holder volume (m³)	3·21	2·85	1·09	1·02
Digester diameter (m)	1·98	2·59	1·45	1·75
Digester depth (m)	4·88	2·44	2·72	1·52
Digester depth-diameter ratio	2·46	0·94	1·88	0·87
Digester volume (m³)	15·02	12·85	4.49	3·65
Capital cost of plant (Rs)	8100	4765	3250	2355
Relative costs	100	58·80	100	72·50
Daily loading (kg fresh dung)	150	150	50	50
Mean temperature	27·60	27.60	*	27·60
Daily gas yield (m³/day)	4·28±0·47	4·89±0·60	*	1·93±0·38
Actual capacity/rated capacity	75·6%	86·4%	*	113·7%
Gas yield (cm³)/g fresh dung	28·5±3·2	32·7±4·0	*	38·5±7·6
Improvement in gas yield	—	+14·2%	*	*

*Since a 60 cubic ft/day plant of KVIC design has not been studied under identical conditions as the corresponding ASTRA plant, values have not been inserted for the performance of the former type of plant.

digester of diameter 6·5 ft (2 m) and 16·5 ft (5 m) respectively. These dimensions are sufficiently close to the dimensions recommended by the designers (cf. table 1) to conclude that the basis for the design of conventional plants has been successfully elucidated here.

Evidently, the diameters of the gas holders of conventional plants are chosen by minimising the gas holder cost; then, the diameters of the digesters are set equal to (actually, slightly greater than) the diameters of the gas holders; and finally, the digester diameters along with the volumes of these pits, determine the depths of the digesters. The whole procedure leads to the narrow and deep digesters characteristic of conventional plants. Further, the fact that these characteristics have been explained quite simply with cost-minimisation arguments indicates that the dimensioning of conventional plants has little to do with stratification and temperature influences which incidently have not been observed in the present study (cf. part I of this paper). The latter conclusion is confirmed by the fact that shallow horizontal digesters function quite satisfactorily without being as deep as the conventional digesters.

3. Optimisation based on minimising capital cost of plant

If cost minimisation is the crucial factor in optimising the dimensions of biogas plants, then it is clear that the total capital cost of the gas holder *and* the digester, must be taken into account and not the former alone. In other words, the optimisation must be based on minimising R (cap) given by

$$R\,(\text{cap}) = R + R', \tag{16}$$

where R and R' are the capital costs of the gas holder [cf. equation (2)] and digester respectively.*

The cost of the digester involves four contributions (i) R'_b, the cost of the base of the digester pit, (ii) R'_s, the cost of its sides, (iii) R'_p, the cost of the central partition wall separating the digester pit into the inlet and outlet sides, and (iv) R'_e, the cost of excavating the digester pit. Thus,

$$R' = R'_b + R'_s + R'_p, + R'_e. \tag{17}$$

The civil engineering costs associated with these four contributions may be elaborated further in the following way (using the assumption $D' \approx D$, i.e., the diameters of the digester and gas holder are almost equal)

$$R' = \frac{\pi D^2 t' u'}{4} + \pi Dh' t' u' + Dh' t' u' + \frac{\pi D^2 h' u_e}{4}, \tag{18}$$

where h' is the depth of the digester, t', the thickness of the masonry (assumed for simplicity to be the same for the base, sides and partition wall), u', the unit cost of

*The total capital cost here excludes the cost of inlet and outlet tanks, pipes, etc.

6

the masonry in Rs/unit area, and u_e, the unit cost of excavation in Rs/unit volume. Using the symbol

$$\beta = t' u', \tag{19}$$

and expressing h' in terms of $D' = D$ with the aid of equation (13), the result is

$$R' = (\pi D^2\beta/4) + (8\beta\phi C/D)\left(1 + \frac{1}{\pi}\right) + 2\phi u_e' C. \tag{20}$$

Combining this expression with equation (4), the total capital cost of the digester plus gas holder becomes

$$R\text{ (cap)} = \frac{4C}{D}\left\{\alpha\gamma + 2\beta\phi\left(1 + \frac{1}{\pi}\right)\right\} + \frac{\pi D^2}{4}(\alpha + \beta) + 2\phi u_e' C$$

$$= (4\delta C/D) + (\pi\epsilon D^2/4) + 2\phi u_e' C, \tag{21}$$

where $$\delta = \alpha\gamma + 2\phi\beta\left(1 + \frac{1}{\pi}\right), \tag{22}$$

and $$\epsilon = \alpha + \beta. \tag{23}$$

In minimising the objective function R (cap), it shall be assumed, *as a first approximation*, that the unit civil engineering costs of masonry construction and excavation are independent of depth*, i.e., $u' \neq f(h')$ and $u_e' \neq f(h')$.

On this basis, by differentiating R (cap) with respect to D and setting the result equal to zero, the diameter** $D_A' = D_A$ corresponding to the minimum total capital cost turns out to be

$$D_A' = D_A = (8\delta/\pi\epsilon)^{1/3} C^{1/3}, \tag{24}$$

and the height to depth ratio for a digester pit optimised in the above manner is

$$h_A'/D_A' = h_A'/D_A = \phi\epsilon/\delta. \tag{25}$$

For the same values of γ and ϕ that were used for conventional plants [cf. equation (15)], and using present costs of steel fabrication and masonry construction to assign the values: α = Rs 22/ft^2 (Rs 237/m^2) and β = Rs 6·75/ft^2 (Rs 73/m^2), it turns out

*Even if the variation of unit costs with depth is taken into account, e.g., by writing $u' = u'^0 + k_1 h$ to correspond with civil engineering rates, the basic conclusions are unaffected, though the mathematics gets slightly more complicated, as is shown in appendix 1.

**The subscript A is used to indicate that the diameter, D_A', depth, h_A', etc correspond to the modified design of biogas plants developed in this work as part of the ASTRA programme of the Indian Institute of Science.

that ϵ = Rs 28·75/ft^2 or Rs 309/m^2 and δ = Rs 39·4/ft^2 or Rs 424/m^2. For these values,

$$h'_A/D_A \approx 1{\cdot}1, \tag{26}$$

i.e., the optimised dimensions correspond to *wide and shallow digesters with depths almost equal to the diameters*, when the total capital cost of gas holder and digester is minimised.

The gas holder height is determined, as stated earlier, by the gas storage that is required—cf. equation (7)—i.e.,

$$h_A = 4\,\gamma\, C/\pi\, D_A^2. \tag{27}$$

The differences in the dimensions of conventional plants [cf. equations (6), (7), (13) and (14)] and those of plants based on minimising the total capital cost [cf. equations (24), (25) and (26)] lead to differences in the comparative costs of the plants. The total cost of conventional narrow and deep plants can be obtained from

$$R_K\,(\text{cap}) = R_K + R'_K, \tag{28}$$

by introducing expressions (8) and (20) for R_K and R'_K respectively and using equation (6) to substitute for D in equation (20). The result is

$$R_K\,(\text{cap}) = \pi^{1/3}\,\gamma^{2/3}\,\{3\alpha + \beta\,[1 + (4\phi/\gamma)\,(1 + 1/\pi)]\}\,C^{2/3} + 2\phi u'_e C, \tag{29}$$

which can be further simplified thus:

$$R_K\,(\text{cap}) = (\pi/\gamma)^{1/3}\,(\epsilon\gamma + 2\delta)\,C^{2/3} + 2\phi u'_e C. \tag{30}$$

On the other hand, when the capital cost of the gas holder *plus* digester is minimised, this capital cost is given by substituting for D in equation (21) with the aid of equation (24):

$$R_A\,(\text{cap}) = (27\pi\epsilon\delta^2)^{1/3}\,C^{2/3} + 2\phi u'_e C. \tag{31}$$

A comparison of the capital costs of the two types of plants can be obtained by inserting some numerical values. For example, with $\gamma = 0{\cdot}6$, ϵ = Rs 28·75/ft^2, δ = Rs 39·4/ft^2, $\phi = 1{\cdot}53$ (for $t_a = 52$ and $Y = 34$), the expressions are

$$R_K\,(\text{cap}) = 166{\cdot}7\; C^{2/3} + 1{\cdot}2\; C, \tag{32}$$

$$R_A\,(\text{cap}) = 155\; C^{2/3} + 1{\cdot}2\; C, \tag{33}$$

showing that the latter type of plants are about 7% cheaper even assuming that civil engineering costs of excavation and construction, i.e., u'_e and u' (i.e., β, ϵ and δ) are independent of depth, which is not the case. If this depth-dependence of civil engineering costs is taken into account, a greater cost-reduction is achieved.

4. Performance of modified plants

To test the new approach to optimising the dimensions of biogas plants developed above, it was decided to build plants with modified dimensions and to compare their performances with conventional plants of KVIC design.

In this process, the value to be chosen for the detention time t_d and therefore, the volume of the digester pit [cf. equation (1)] was also considered. The detention time affects both the capital and operational costs of a biogas plant: a longer detention time leads to greater gas yield from a given input of volatile solids, but also to a greater digester volume and therefore greater capital cost; a shorter detention time results in a cheaper digester, but also to a smaller gas yield and therefore greater loss of operational revenues. To be rigorous, the detention time must be determined by minimising the sum of the capital and operational costs, or maximising the return from the plant given by the net operational revenue minus the capital charges. This approach to choosing the detention time—apparently not attempted hitherto—will be described in a subsequent publication (Subramanian & Reddy, to be published.)

In the present work, an empirical alternative was adopted. The detention time was chosen from the results of previous workers who have shown that for the mean temperatures prevalent at Bangalore, i.e., about 25°C, a detention time of about 35 days is valid (Meynell 1976).

Using the values $\gamma = 0{\cdot}5$, $\alpha =$ Rs $22/\text{ft}^2$, $\beta =$ Rs $6{\cdot}75/\text{ft}^2$, $t_d = 35$ days, $\rho_{sl} = 1{\cdot}03\ \text{g/cm}^3$, $Y = 34\ \text{g/cm}^3$, i.e., $\phi = 1$, $\epsilon = 28{\cdot}75$ and $\delta = 28{\cdot}8$, a 200 cubic ft/day ($5{\cdot}66\ \text{m}^3$/day) plant was designed with the aid of equations (24), (25) and (27). In addition, a 60 cubic ft/day ($1{\cdot}7\ \text{m}^3$/day) plant was also designed on exactly the same basis, except that $\gamma = 0{\cdot}6$. The dimensions of these ASTRA plants are given in table 1, which also includes for comparison purposes the dimensions of the conventional plants of KVIC design described in part I and in the literature.

The ASTRA plants were constructed in January 1979 and charged in February 1979. Owing to difficulties in the procurement of dung supply, a rigorous comparison of the performances of the conventional and modified plants could be made only from 7 April 1979.

The results of this comparison given in table 1 lead to the following conclusions.

(i) The ASTRA plants are significantly cheaper than the conventional plants—the cost reduction of 25–40% being achieved by optimisation of dimensions and choice of realistic detention times.

(ii) The performances of the ASTRA plants are as good as—in fact, slightly better than—those of the conventional plants. For example, for the same daily loading of 150 kg fresh dung into the 200 cubic ft/day plants, the ASTRA plant gives a 14% greater gas yield per unit weight of input material despite it being 40% cheaper.

(iii) The shallow digesters of the ASTRA plants are more convenient from the civil engineering point of view, and are a great advantage in situations where the water table is high. Besides, the wider plants reduce the strength requirements of foundations.

5. Conclusions

(i) The ASTRA plants described above have been designed, constructed and operated on the assumption that stratification does not occur to any significant extent in biogas plants, i.e., there is uniformity of temperature and density inside the digesters. This assumption has been validated by the actual performances of the ASTRA plants which are in fact slightly better than the performances of conventional plants.

(ii) In view of the fact that there are no technical reasons, for example, stratification, which necessitate narrow and deep digesters, the optimisation of plant dimensions must be based merely on cost minimisation grounds alone.

(iii) For given materials and techniques of construction of the gas holder and digester and given conditions of operation, three levels of optimisation of plant dimensions are possible:

Level 1: *Optimisation:* Dimensions based on minimisation of gas holder cost—this leads to conventional plants of the KVIC design.
Level 2: *Optimisation:* Dimensions based on minimisation of capital cost of gas holder + digester—this leads to the ASTRA plants described in this part of the paper.
Level 3: *Optimisation:* Dimensions based on a detention time corresponding to minimum total capital + operating costs—this may lead to further modifications if the detention time thus derived differs from that chosen in the Level 2 optimisation.

(iv) If the detention time has been chosen on the basis of previous work, then Level 2 optimisation leads to three simple expressions for the plant dimensions

(a) $$D_A \approx D'_A = (8\,\delta/\pi\,\epsilon)^{1/3}\,C^{1/3}, \tag{24}$$

(b) $$h_A = (4\,V/\pi\,D_A^2) = (4\,\gamma\,C/\pi\,D_A^2), \quad (\gamma = \text{fraction of daily gas yield to be stored}), \tag{27}$$

(c) $$h'_A = 4\,V'/\pi\,D_A^2 = (\phi\,\epsilon/\delta)\,D_A. \tag{25}$$

As a zeroth approximation, even simpler thumb-rules can be stated for biogas plants with masonry digesters and floating mild-steel gas holders.

(a) $$D \approx D' \approx 1{\cdot}5\,C^{1/3}, \tag{34}$$

(b) $$h \approx 0{\cdot}3\,C^{1/3}, \tag{35}$$

(c) $$h' \approx D'. \tag{36}$$

(v) The expression for the cost of biogas plants [cf. equation (31)] show that plant costs do not increase linearly with plant capacity. In other words, there are definite economies of scale in biogas plants. As a first approximation excluding excavation costs, the total cost of N plants each of capacity (C/N) is $N^{1/3}$ times the cost of one plant of capacity C.

(vi) These same expressions also define a clear-cut strategy for cost reduction in biogas plants. The crucial parameters which need to be reduced are t' (thickness of masonry in digester), γ (fraction of daily gas yield which is stored), u and u' (the costs per unit area of gas holder and digester respectively), and t_d (the detention time). The reduction of u and u' is best achieved through the use of alternative materials and/or techniques of construction. In contrast, the reduction of t_d must be accomplished by operation of biogas plants under optimum conditions, for example, at the optimum temperature of 35°C (for mesophilic bacteria) instead of at lower ambient temperatures. A simple way of increasing the temperature inside the digester is described in part IV of this paper.

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Appendix 1

Calculation of dimensions and costs assuming $u' = f(h')$

The calculation of dimensions and costs taking into account the dependence of the u', the unit cost of masonry construction, upon h', the digester depth is achieved by introducing a depth-dependence into the parameters δ and ϵ into equation (21), viz.,

$$R\,(\text{cap}) = (4\delta\, C/D) + (\pi\, \epsilon\, D^2/4) + (2\,\phi\, u'_e\, C).$$

Writing $u' = u'_0 + k_1\, h'$, the parameters become

$$\beta = t'\, u'_0 + k_1\, t'\, h' = \beta_0 + k_1\, t'\, h',$$

$$\epsilon = \alpha + \beta_0 + k_1\, t'\, h' = \epsilon_0 + k_1\, t'\, h',$$

$$\delta = [\alpha\,\gamma + 2\,\phi\,(1 + 1/\pi)\,\beta_0] + (2\,\phi\,(1 + 1/\pi)\,k_1\, t']\, h' = \delta_0 + k_2\, h'.$$

Introducing these values into equation (21), using equation (13) for h', and ignoring the excavation cost by virtue of its negligible contribution to the total cost, the result is:

$$R\,(\text{cap}) = (\pi\, \epsilon_0/4)\, D^2 + (4\delta_0\, C)\, 1/D + (32k_2\,\phi\, C^2/\pi)\,(1/D^3) + 2k_1\, t'\,\phi\, C.$$

Differentiating this equation and setting the result equal to zero,

$$d\,R\,(\text{cap})/dD = (\pi\, \epsilon_0/2)\, D - (4\delta_0\, C)\, 1/D^2 - 3\,(32k_2\,\phi\, C^2/\pi)\, 1/D^4 = 0,$$

or $$(\pi\, \epsilon_0/2)\, D^5 - (4\delta_0\, C)\, D^2 - 3\,(32k_2\,\phi\, C^2/\pi) = 0.$$

This equation can be solved by the Newton-Raphson method for a $C = 200$ cubic ft/day (5·66 m^3/day) plant using the values $\alpha = 22$, $\beta_0 = 6{\cdot}75$, $\epsilon_0 = 28{\cdot}75$, $\delta_0 = 40{\cdot}41$, $\phi = 1{\cdot}53$, $k_1 = 0{\cdot}25$ and $t' = 1$.

The result is $D^* = 3{\cdot}15$ m from which it follows that $h'^* = 2{\cdot}22$ m and $h'^*/D^* = 0{\cdot}7$, in comparison with the first-approximation $[u' \neq f(h')]$ values of $D_A = 2{\cdot}73$ m, $h'_A = 2{\cdot}97$ m and $h'_A/D_A \approx 1{\cdot}1$. Hence, by taking into account the dependence of u' on h', the optimised digesters become even more wide and shallow.

The cost differences arising from the functional dependence of u' on h' can be calculated from an alternative form of equation (21), viz., (after ignoring excavation costs)

$$R\,(\text{cap}) = \underbrace{[(4\,\alpha\,\gamma\,C/D) + (\pi\,\alpha\,D^2/4)]}_{\text{Gas holder}} + \underbrace{[(\pi\,D^2\beta/4) + Dh'\,\beta\,(\pi + 1)]}_{\text{Digester}}. \qquad \text{(A.1)}$$

If $\beta = \beta_0 + k_1 t' h'$ and $\beta_0 = 6{\cdot}75$, $k_1 = 0{\cdot}25$, $t' = 1$ and $h' = 7{\cdot}28$ ft (2·22 m), the capital cost for $\alpha = 22$ and $\gamma = 0{\cdot}6$, is Rs 6250. This should be compared with Rs 5400 (excluding excavation costs) obtained by assuming $u' \neq (h')$, $\beta = \beta_0 = 6{\cdot}75$ and equation (31) for R (cap).

If instead of assuming that u', and therefore β, is a continuous function of h', it is assumed that u' is a staircase function of h', so that $u' = 6{\cdot}75$ for $0 < h' \leqslant 6$ ft and $u' = 10{\cdot}75$ for 6 ft $< h' \leqslant 12$ ft, and that D and h' are obtained by assuming no depth-dependence of u', i.e., $D = 2{\cdot}73$ m and $h' = 2{\cdot}97$ m, it turns out that R (cap) is Rs 6232. Hence, by assuming this staircase function for u', it is possible to calculate D and h' without taking into account the depth-dependence of u' of h', and still obtain a biogas plant cost which is within 0·3% of the cost obtained by assuming $u' = u'_0 + k_1 t' h'$ and calculating D and h' with this assumption.

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Studies in biogas technology. Part III. Thermal analysis of biogas plants

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Abstract. A thermal model for a conventional biogas plant has been developed in order to understand the heat transfer from the slurry and the gas holder to the surrounding earth and air respectively. The computations have been performed for two conditions: (i) when the slurry is at an ambient temperature of 20°C, and (ii) when it is at 35°C, the optimum temperature for anaerobic fermentation. Under both these conditions, the gas holder is the major "culprit" with regard to heat losses from the biogas plant. The calculations provide an estimate for the heat which has to be supplied by external means to compensate for the net heat losses which occur if the slurry is to be maintained at 35°C. Even if this external supply of heat is realised through (the calorific value of) biogas, there is a net increase in the biogas output, and therefore a net benefit, by operating the plant at 35°C. At this elevated temperature, the cooling effect of adding the influent at ambient temperature is not insignificant. In conclusion, the results of the thermal analysis are used to define a strategy for operating biogas plants at optimum temperatures, or at higher temperatures than the ambient.

Keywords. Thermal analysis; biogas plant; heating requirement; heat transfer; elevated temperature operation; heat loss from gas; slurry.

1. Introduction

It has been established (Meynell 1976) that the rate of gas yield, and the detention time necessary to anaerobically digest organic wastes in a biogas reactor, are favourable functions of the temperature in the digester. In the mesophilic range (5–40°C), the reaction rate constant approximately doubles for every 10° to 15°C increase in temperature and has a maximum value at 35°C. Thus, the operation of biogas plants at higher temperatures (than the ambient) would be beneficial in increasing the gas yield, as well as in reducing the detention time for the charge, so that for a required gas production rate, the size, and therefore cost, of the plant can be reduced substantially. Further, in locations where ambient temperatures fall below 10°C in winter, biogas production decreases drastically or may even stop altogether—this problem can also be overcome by operation of biogas plants at elevated temperatures. Thus, heat from external sources must be supplied to biogas plants (Prasad *et al* 1974) if they are to operate at an optimum temperature of 35°C, or at a temperature above the ambient in order to assure at least some gas production in winter.

During the operation of a conventional biogas plant (cf. part I of this paper), it was found that the temperature of the slurry within the digester was not significantly different from the mean ambient temperature. From this observation, it can be concluded that the rate of internal heat generation from the nominally exothermic anaerobic reaction is negligible.

A list of symbols appears at the end of the paper.

A simple thermal model of the biogas plant has been developed for estimating the temperatures of some of the components of the biogas plant, viz., the gas holder, the gas inside the holder, and the slurry. Once the temperatures are calculated, the heat losses from the biogas plant and the external energy inputs necessary to operate the plant at any desired temperature can be found. Computations of these quantities have been carried out for the biogas plant described in part I of this paper, using the data corresponding to the locally prevailing meteorological conditions.

2. Thermal analysis of conventional biogas plants

A thermal model of the biogas plant has been developed mainly for predicting the diurnal variations of the temperatures of the gas holder drum which is exposed to the ambient atmosphere, and of the slurry which is enclosed in the digester pit. The heat lost or gained over a day from the gas holder and the slurry can then be computed.

By assuming that the major components of the biogas plant and its environment (figure 1), viz., (i) the gas holder drum, (ii) the gas within the drum, (iii) the slurry, (iv) the ambient air and (v) the earth surrounding the digester well, are each isothermal, simple energy-conservation relations can be derived for the biogas plant. The assumption of isothermality for these components is justified for the following reasons:

(i) Measurements of temperature at several locations on the gas holder drum indicated uniformity of temperature to within $\pm 0{\cdot}5°C$.
(ii) As stated in part I of this paper, the temperature of the slurry is uniform showing no stratification.

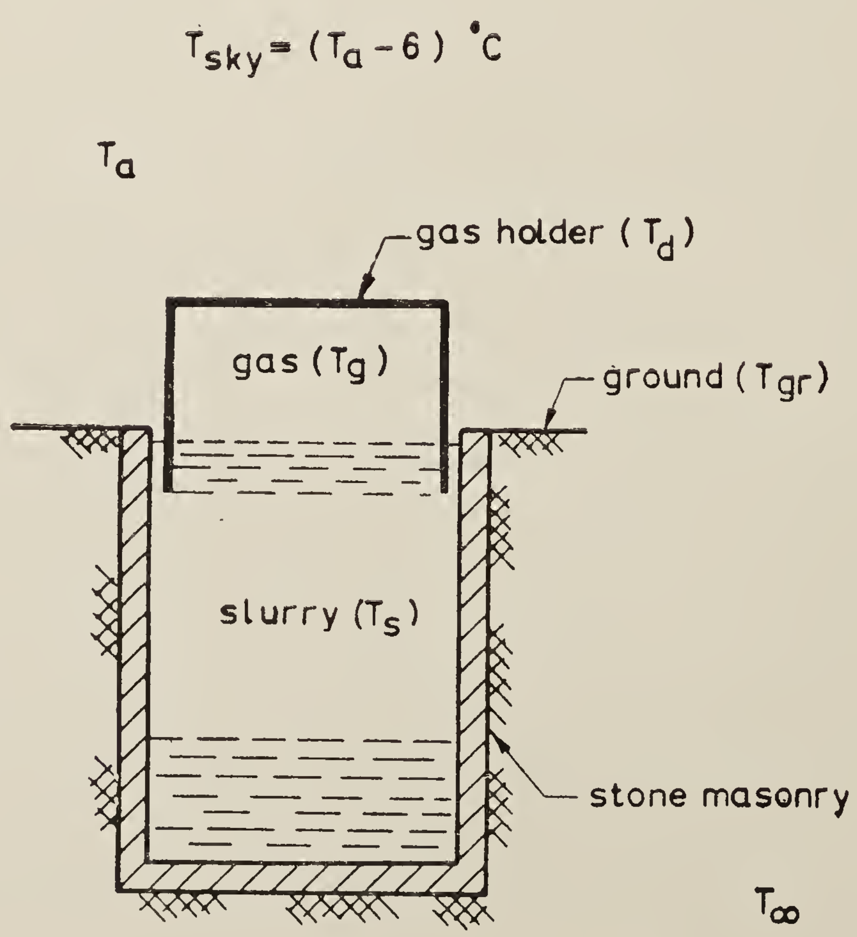

Figure 1. Cross-section of a conventional KVIC design of a biogas plant

(iii) The diurnal fluctuations of temperature at the surface of the earth are fully damped out within the first few centimeters from the surface and only seasonal changes are felt at the depths of interest to us (Eckert & Drake 1974; Ramakrishna Rao *et al* 1977). So the soil temperature can be taken to be constant over short periods (like a day), while the slower, i.e., seasonal, variations are accounted for by changing the value of this temperature during different months.

The energy conservation relation for the gas holder is given by

$$(mC_p)_D \frac{dT_D}{dt} = [I_{s,h}\,\alpha A_t + I_{s,v}\,\alpha A_s] + \sigma\epsilon\,[A_t\,(T^4_{\text{sky}} - T^4_D)$$

$$+ \tfrac{1}{2}A_s\,(T^4_{\text{sky}} + T^4_{\text{Gr}} - 2T^4_D)] + \sigma\epsilon\,A_t\,(T^4_S - T^4_D)$$

$$- [h_1 A_t\,(T_D - T_A) + h_2 A_s\,(T_D - T_A)]$$

$$- [h_3\,(A_t + A_s)\,(T_D - TG)]$$

$$- h_4\,A_s\,(T_D - T_S). \tag{1}$$

Here, the term on the left is the energy storage in the gas holder, whereas the first term on the right is the solar influx, the second is the radiative exchange of the outer surface of gas holder with the sky and ground, the third is the radiative exchange of the inside of the drum with slurry. The negative terms represent convective exchange, the first bracketed term shows the heat lost by convection to air from the outside surface of the gas holder, the second shows the heat lost to gas inside the gas holder and the last term shows the heat lost to slurry through the skirt of the gas holder that is immersed inside the slurry. Since the gas holder rides up and down depending on gas accumulated inside it, it has been assumed, for convenience, that the gas holder is always half full (i.e., half the height is exposed to atmosphere, while the bottom half is immersed inside the slurry). The values of heat transfer coefficients used in the computation have been tabulated in table 1.

A similar energy conservation relation can be derived for the slurry (see appendix):

$$(mC_p)_S \frac{dT_S}{dt} = \sigma\epsilon\,(T^4_D - T^4_S)\,A_t + h_4\,A_s\,(T_D - T_S)$$

$$+ h_s\,A_t\,(T_G - T_S) - h_6\,A_w\,(T_S - T_\infty), \tag{2}$$

where the last term on the right is the heat lost from slurry through the side walls of the digester pit.

The energy conservation relation for the gas can be written thus:

$$h_3\,(A_t + A_s)\,(T_D - T_G) = h_5\,A_t\,(T_G - T_S), \tag{3}$$

Table 1a. Coefficients for convective heat transfer

Coefficients	Description	Value of coefficient kcal/m² hr °C
h_1	The top horizontal of gas holder to air (Average wind velocity taken as 5 km/hr)	$2\cdot14\,(\Delta T)^{1/4}$ for natural convection $0\cdot86\,(5\cdot7+3\cdot8V)$ for forced convection V=wind velocity m/s
h_2	Gas holder side surface to air	$1\cdot139\,(\Delta T/d)^{1/4}$ for natural convection $=8\cdot24$ for $V=2\cdot8$ m/s for forced convection
h_3	Gas holder inner surface to gas	$3\cdot52 = h_4$ = gas to slurry
h_5	Gas holder (that is immersed in slurry) to slurry	5·00
h_6	Overall heat transfer coefficient for transfer from slurry to ground $=\left[\frac{1}{h'_6}+\frac{l_1}{k_1}+\frac{l_2}{k_2}+\frac{l_3}{k_3}\right]^{-1}$ (l, k are the conduction thickness m and thermal conductivity kcal/m hr °K)	$h'_6=50$ (computed by taking the slurry properties as that of water. The Grashof number $Gr=g\beta\Delta Th^3/\nu^2\simeq10^8$ and $h'_6=50$ as a high estimate*) l_1, k_1 refer to cement plaster ($l_1=0\cdot024$, $k_1=0\cdot26$) l_2, k_2 refer to stone masonry ($l_2=0\cdot23$, $k_2=2\cdot16$) l_3, k_3 refer to earth ($l_3=0\cdot25$, $k_3=0\cdot48$)

*Berkat H Z & Clark J A (1966)

Table 1b. Coefficients for radiative heat transfer

Coefficients	Description	Value of the Coefficient
α	Absorption coefficient of gas holder for solar radiation	0·9
α'	$=\alpha\,(1-\rho)$ where ρ is the reflectivity	$\rho=0\cdot1$; $\alpha'=0\cdot81$
ϵ	Emissivity of gas holder at long wavelength	0·9
ϵ'	Effective emissivity of gas holder with transparent cover	$\epsilon'=\left[\frac{1}{\epsilon}+\frac{1}{\epsilon_{\text{glass}}}-1\right]^{-1}$ $\epsilon_{\text{glass}}=0\cdot9$

wherein the energy storage term $(mC_p)_G\,(dT_G/dt)$ is taken as negligible because $(mC_p)_g$ is very small for the gas. No radiation terms have appeared in this equation because it is assumed that the gas is transparent to radiation. By rearranging the terms, equation (3) becomes

$$T_G = aT_D + bT_G\,. \tag{4}$$

In these relations, quantities like the solar influx terms $I_{s,h}$, $I_{s,v}$, and the ambient temperature which are functions of time t, have to be supplied. Since meteorological data are normally available only as daily or monthly average solar influx and as

daily minimum and maximum temperatures, some kind of model is essential in order to obtain the diurnal variation of solar influx and temperature. Here, the NBS-LD programme NBS-BSS-96-1977 which predicts the hourly solar influx from the given monthly average solar irradiation, and the programme NBS-BSS-71-1975 which predicts the hourly ambient temperatures from the given minima and maxima of the daily temperature, have been utilised.

For reducing the time required to complete the computations, a quasi-steady state is assumed to exist and temperatures are computed for 1-hr intervals. Furthermore, for simplicity of computation, 24-hr periods are taken, and it has been assumed that, in any such period, the net energy stored in the system is zero. In other words the temperatures T_D, T_G and T_S are constrained to return to their starting values at the end of a 24-hr period. This is equivalent to

$$\int_{24\text{ hr}} (\text{Rate of heat input})\, dt = \int_{24\text{ hr}} (\text{Rate of heat storage in gas holder} + \text{slurry})\, dt + \int_{24\text{ hr}} (\text{Rate of heat loss})\, dt.$$

The computations were carried out on an IBM 360 computer and involved iterations until the initial values of T_D and T_S agreed with the final values of T_D and T_S after one 24-hr period.

The results of such a calculation are shown in figure 2 for the month of October in Bangalore. It is to be noted that the computed values of temperature depend very heavily on the values of heat transfer coefficients used. For example, the convective loss coefficients such as h, have a strong dependence on the wind velocity which is constantly varying, but it has been taken to be constant with an average value of 5 km/hr for Bangalore. Another parameter which influences the results considerably is the solar influx term. The presence or absence of clouds can make a significant change in the solar incidence on the gas holder. In figure 2 are also shown the

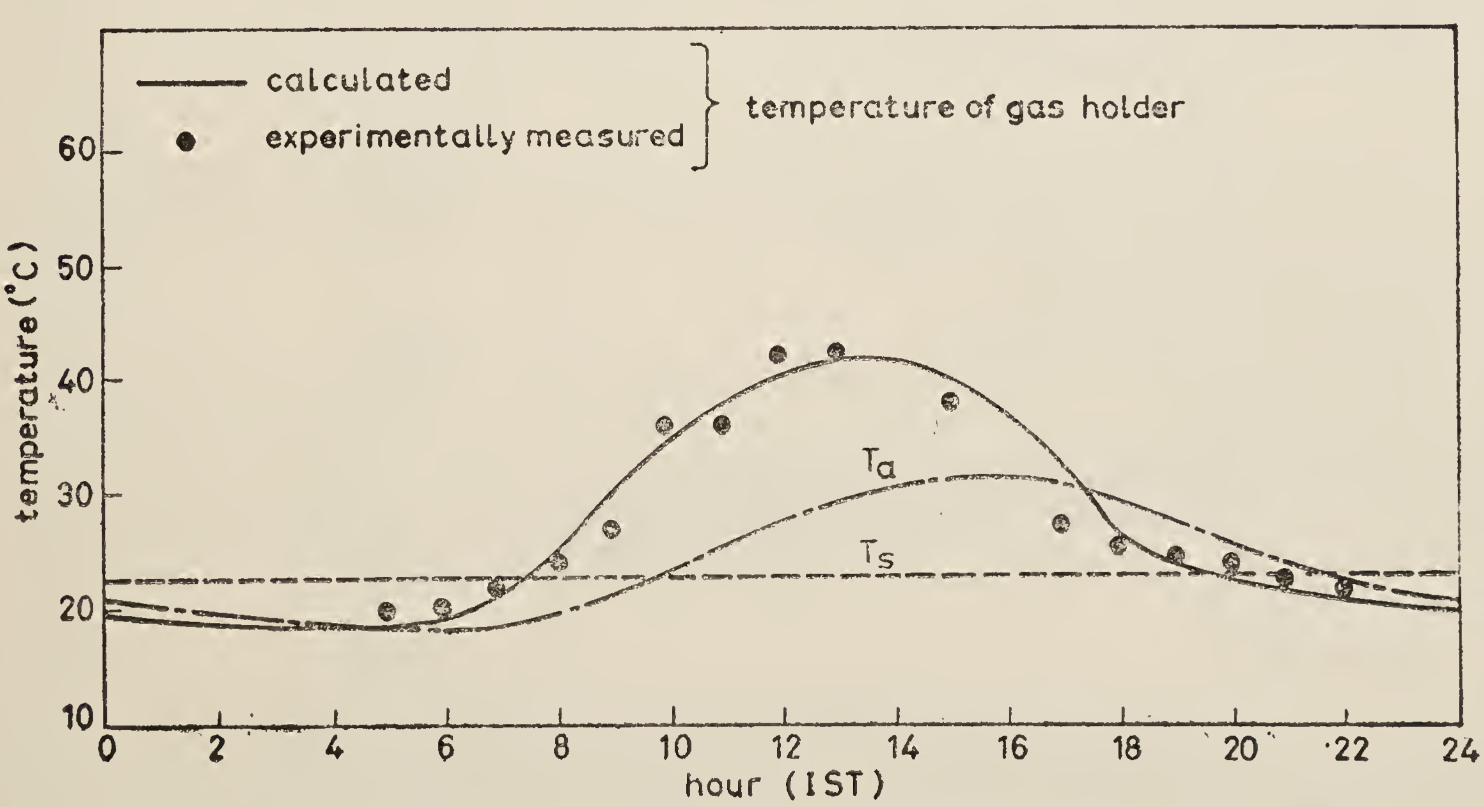

Figure 2. Variations of gas holder, slurry and ambient air temperatures

experimentally measured values of the gas holder temperature, which agree quite well with the computed values, thus implying that the values chosen for the heat transfer coefficients are representative of the real system. As can be observed, the slurry temperature does not fluctuate very much during the day, and its value reflects closely the average ambient temperature, which again is in agreement with the measured slurry temperatures (cf. part I of this paper).

3. Results and discussion

After the temperatures were computed (see figure 2), the heat losses from the gas holder and slurry were calculated. The calculations were repeated for the case where the slurry is maintained at 35°C. The results are presented in table 2 and figure 3, from which several important conclusions can be drawn.

(i) If no attempt is made to intervene and raise the slurry temperature above the ambient temperature, the heat loss from a conventional biogas plant of KVIC design occurs predominantly from the gas holder. Further, almost 54% of the total heat loss occurs from the top of the gas holder.

(ii) If the slurry is considered to be at 35°C, the optimum temperature for anaerobic fermentation, the total heat loss from the biogas plant increases by a factor of 1·8 compared to the heat loss when the slurry is at an ambient temperature of 20°C. Though the heat loss from the slurry to the ground increases to about 31% when the slurry temperature is elevated from 20°C to 35°C, even at this elevated temperature, the heat loss from the gas holder is 59% of the total heat loss, and the top of the gas holder accounts for 30% of the total.

Table 2. Results of computations of heat input and losses

	Conventional design*	Slurry maintained at 35°C*
Heat content of slurry (kcal/°K)	14,340	14,340
Heat content of gas holder (kcal/°K)	36	36
Daily heat loss from gas holder (kcal)		
Roof	10,065	11,252
Side	9,527	10,730
Total	19,592	21,982
Daily heat loss from slurry to ground (kcal)	−958	11,818
Charge cooling loss (kcal/day)	—	3,660
Total heat loss from plant† (kcal/day)	18,634	37,460
Solar influx (kcal/day)	18,652	18,652
Net heat loss (kcal/day)	—18	18,810
Gas required to compensate for net heat loss (m^3/day)	—	3·48
Percentage of gas yield required to compensate for net heat loss	—	30·8%
Net gas yield (m^3/day)	5·66	7·84
Increase in net gas yield	—	39·8%
Gas yield (m^3/day)**	5·66	11·32

*These refer to a 200 cubic ft/day (5·66 cubic m/day) plant of dimensions given in part I of this paper
**For both cases daily charge loading rate is the same
†Calculations are for the month of January at Bangalore

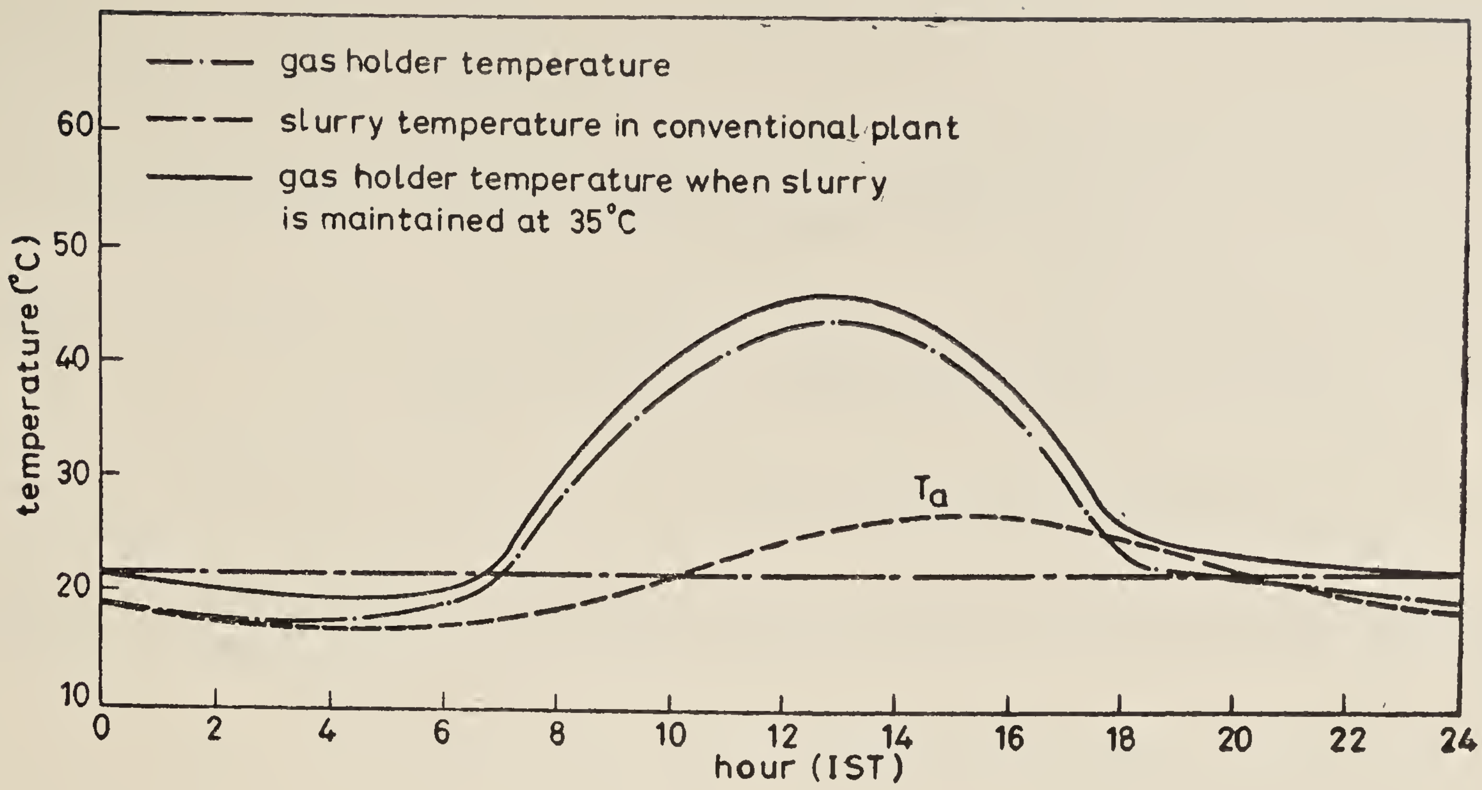

Figure 3. Variation of gas holder slurry and ambient air temperatures for the conventional biogas plant and for the case when slurry is heated to 35°C.

(iii) The daily charging of a 35°C plant with a "cold" mixture of cowdung and water at ambient temperature constitutes a heat loss that is not negligible. Taking the daily charge to consist of 122 kg of cattle dung and 122 kg of water at 20°C, the amount of energy required to raise this charge from 20°C to 35°C is 3660 kcals, i.e., about 10 % of the total heat loss. Thus, there is a cooling effect of a cold charge.

(iv) For the slurry to be maintained at 35°C, heat must be supplied to compensate for the net heat loss from the plant. Assuming that the biogas output will double when the slurry temperature is increased from 20°C to 35°C, only about 30 % of the calorific value of this increased quantity of biogas is necessary (ignoring gas utilisation losses) to compensate for the net heat losses from a 35°C plant. Even after utilising this 30 % of the gas output, an approximately 40 % increase in net gas yield is achieved by operating a biogas plant at 35°C. Thus, there are substantial advantages in operating biogas plants at optimum temperatures, instead of leaving them to the 'mercy' of the environment.

(v) The operation of biogas plants, preferably at the optimum temperature of 35°C, failing which at higher temperatures than the ambient, must be based on the following strategy:

(a) reduction of heat losses from the gas holder, and particularly from its roof;
(b) reduction of the heat losses from cold influent by "hot charging"; and
(c) heating of the plant by external sources.

The authors acknowledge the help of Mr S R Mohan and Prof. K Krishna Prasad in the early phase of these calculations.

Appendix

The reactor in a biogas plant operates as a flow reactor only for the very short period when the plant is charged once a day with the mixture of fresh dung and water. During the rest of the time, there is neither inflow or outflow, and the reactor can be treated as a batch reactor.

For a batch reactor, if there is no internal flow in the slurry, then the conduction equation (Eckert & Drake 1974) describes the heat transfer

$$\rho\, C_p\, (\partial T/\partial t) = \nabla \cdot (k \nabla t) + q,$$

where q is the internal volumetric heat generation term. The boundary conditions are:

(i) at the surface of slurry ($z = 0$)

$$A_t k\, (dT/dZ)_{Z=0} = A_t\, [h_4\, (T_G - T_S) + \sigma\epsilon\, (T_D^4 - T_S^4)\, \dot{m}_E\, L_E],$$

(ii) at $z = Z$: the bottom of pit, $T = T_\infty(Z)$,

(iii) at the circumference of the slurry pit $T\,(r = D/2,\, z) = T_\infty(z)$,

(iv) $(dT/dr)_{r=0} = 0$,

where $m_E L_E$ represents the evaporation loss from the surface.

The situation becomes more complex if there is internal circulation within the slurry itself. For the batch reactor then, the convective boundary layer equations—momentum and energy equations have to be set up and solved (Berkat & Clark 1966) for a cylindrical container.

At the time of charging, the fresh slurry is introduced at the rate of m_{sl}/τ, where m_{sl} is the mass of slurry charged within a period τ. This corresponds to a flow velocity of about 1 cm/s if 250 kg of slurry is charged through a 150 mm diameter tube within 22 minutes. A much lower flow velocity will result within the slurry itself. For a flowing system containing a single phase

$$\rho C_p\, [(\partial T/\partial t) + \mathbf{V} \cdot \nabla T) = \nabla\, (k \nabla T) + q,$$

neglecting viscous dissipation terms. The velocity field will be given by momentum conservation equations which have to be solved along with the energy equations for fully describing the situation. These equations will be extremely complex because the slurry is a multiphase system consisting of solids suspended in a liquid along with gas generation within the mixture. Besides this, since the system is reactive, a mass conservation relation for each of the species is also required. Instead of attempting to solve such a system of equations, a number of simplifications have been made to reduce the complexity of the problem.

The first assumption to be made is that the slurry is isothermal during its batch

operation, i.e. $\nabla T=0$. The internal heart generation q being very small it is neglected. So the energy equation simplifies to

$$(mC_p)_S\,(dT_S/dt) = h_4A_t\,(T_G - T_S) + h_5A_s\,(T_D - T_S)$$

$$+ \sigma\epsilon A_t\,(T_D^4 - T_S^4) - h_6A_w\,(T_S - T_\infty).$$

During the periods of charging, convection terms have to be included. Then

$$(mC_p)_S\,(dT_S/dt) = h_4A_t\,(T_G-T_S) + h_5A_s\,(T_D-T_S) + \sigma\,\epsilon\,A_t\,(T_D^4-T_S^4)$$

$$- h_6\,A_w(T_S-T_\infty) + (m_{sl}/\tau)\,C_p\,(T_{ch}-T_S)\,X(t).$$

where fresh charge loaded at the rate (m_{sl}/τ) at temperature T_{ch} displaces an equal mass of old slurry in the pit. $X(t)$ is a function which is zero at all times when charging is not done but $X(t) = 1$ during such periods when charging is carried out.

In the analysis presented in the paper, $X(t)$ has been equated to zero for the sake of simplicity. The computations have bee carried out for a full cycle of 24 hr. The effect of addition of charge is included by changing the initial condition for the next cycle of 24 hr.

List of symbols

A_s	half of the area of the skirt of gas holder
A_t	area of the top surface of gas holder
A_w	circumferential area of the slurry pit
a, b	constants
C_p	specific heat (kcal/kg °C)
h_1–h_5	convective heat transfer coefficients (kcal/m^2 hr °K)
T	temperature.
t	time
α, α^1	absorptivities at short wavelengths (for solar incidence)
ϵ, ϵ'	emissivities at long wavelengths
σ	Stefan-Boltzman constant

Subscripts

A	ambient
D	gas holder drum
G	gas inside the drum
S	slurry
∞	soil under the surface

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Studies in biogas technology. Part IV. A novel biogas plant incorporating a solar water-heater and solar still

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Abstract. A reduction in the heat losses from the top of the gas holder of a biogas plant has been achieved by the simple device of a transparent cover. The heat losses thus prevented have been deployed to heat a water pond formed on the roof of the gas holder. This solar-heated water is mixed with the organic input for ' hot-charging ' of the biogas plant.

A thermal analysis of such a solar water-heater ' piggy-backing ' on the gas holder of a biogas plant has been carried out.

To test whether the advantages indicated by the thermal analysis can be realised in practice, a biogas plant of the ASTRA design was modified to incorporate a roof-top solar water-heater. The operation of such a modified plant, even under ' worst case ' conditions, shows a significant improvement in the gas yield compared to the unmodified plant. Hence, the innovation reported here may lead to drastic reductions in the sizes and therefore costs of biogas plants.

By making the transparent cover assume a tent-shape, the roof-top solar heater can serve the additional function of a solar still to yield distilled water.

The biogas plant-cum-solar water-heater-cum-solar still described here is an example of a spatially integrated hybrid device which is extremely cost-effective.

Keywords. Biogas plant; solar water-heater; solar still; thermal analysis; hot charging; design modification; gas yield; hybrid device.

1. Introduction

The thermal analysis of biogas plants (cf. part III of this paper) has not only estimated the net benefits of operating these plants at the optimum temperature, but also suggested an approach for realising these benefits. In particular, the analysis has emphasised the importance of

(i) supplying heat by external means,
(ii) charging the plant with a ' hot ' charge,
(iii) reducing heat losses from the gas holder and particularly its roof.

Interestingly enough, the listing of these approaches is in the same order as the magnitude of the efforts which biogas technologists have devoted to them.

Thus, there has been widespread awareness of the first of the above methods (cf Prasad *et al* 1974, Meynell 1976), leading to suggestions such as utilising the heat

derived by burning part of the biogas output, using the exhaust heat from a biogas-driven engine, electrical heating, etc. The importance of ' hot charging ' has also been widely appreciated leading to the erection of separate solar water-heaters providing the hot water to mix with the cold organic input, e.g., cattle dung. But, there has been virtually no attention focussed on the reduction of heat losses from the gas holder, and particularly its roof, perhaps because the importance of this factor has only just been highlighted by the thermal analysis carried out as part of the present studies (cf part III of this paper).

If instead, attention is primarily directed towards reducing heat losses from the top of the gas holder, there is a possibility of devising a totally different approach to the heating of biogas plants. In fact, such a novel technique has been developed and will be described below.

2. Principle of innovation

If a transparent cover is incorporated on the gas holder (like the glass cover on a solar flat-plate collector), much of the convective and radiative heat losses from the gas holder can be reduced whilst only marginally affecting the solar radiation falling on the gas holder. Since the heat losses from the gas holder constitute a very significant part (as much as 60% at times) of the total heat loss from the biogas plant, any reduction in the former would lead to a saving in the external energy input that would be required to operate the plant at elevated temperatures. A simple but novel technique of achieving this reduction in heat loss from the gas holder has, therefore, been developed (figure 1). By projecting the sides of the gas holder above its top surface a receptacle can be formed for a shallow water pond, and the top of this water container can be covered with a transparent sheet of glass or plastic, so that the whole unit works as a solar water-heater during the day. In such a modified gas holder, the heat losses saved by the introduction of the transparent cover are gainfully deployed towards the heating of the water pond. Further, this heated water can be used for making up of the daily charge, i.e., for ' hot charging ' the plant.

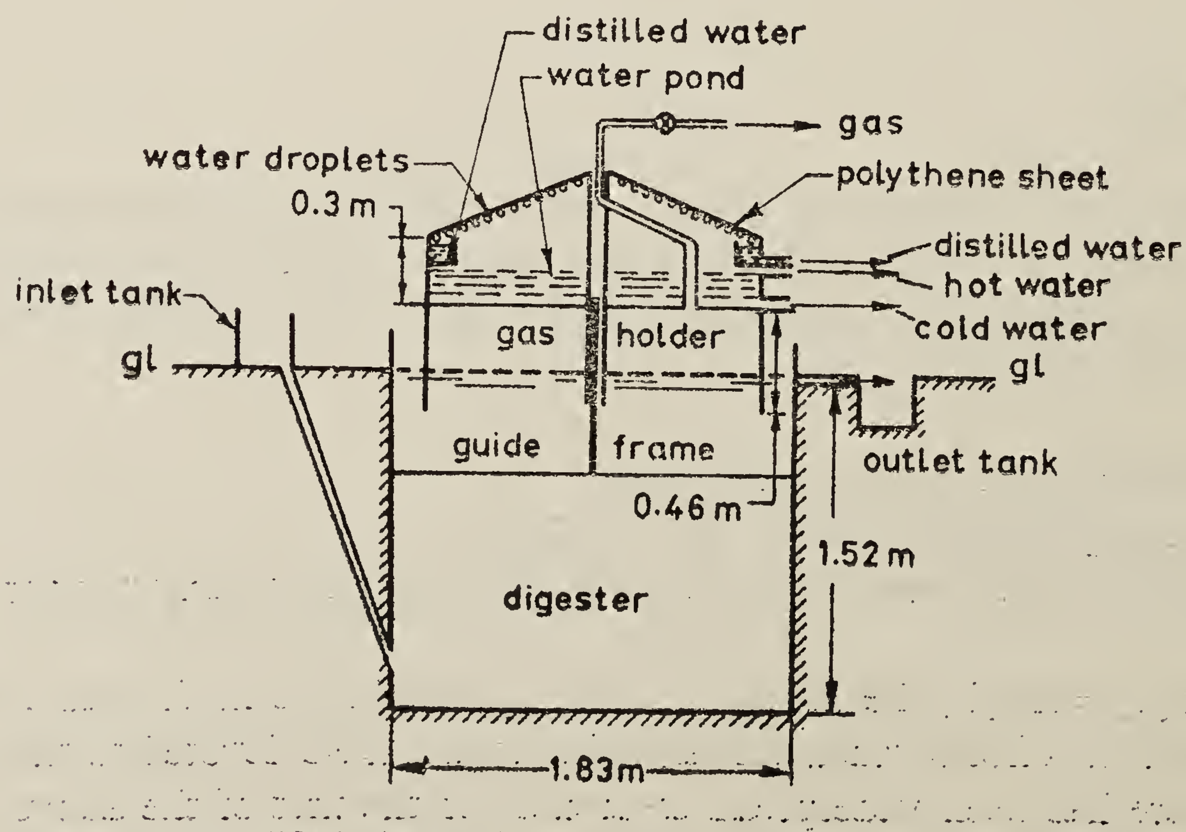

Figure 1. Modified biogas plant

3. Thermal analysis

The thermal model developed in part III of this paper can now be extended to the innovation described above. The differences involve the modified gas holder with a water pond on its roof and a transparent cover over the pond. These features require an alteration of the energy conservation relation for the gas holder. In making this alteration, it will be assumed, for simplicity, that the gas holder and the water in the pond are at the same temperature. Then, the energy conservation relation for the gas holder becomes*

$$[(mC_p)_D + (mC_p)_w] \frac{dT_D}{dt} = [\alpha'(I_{s,h} A_t + I_{s,v} A_s)] + \sigma\epsilon'[A_t(T_{\text{sky}}^4 - T_D^4)$$

$$+ \tfrac{1}{2}A_s(T_{\text{sky}}^4 + T_{\text{Gr}}^4 - 2T_D^4)] + \sigma\epsilon A_t(T_S^4 - T_D^4)$$

$$- [h_1 A_t(T_C - T_A) + h_2 A_s(T_D - T_A)] - [h_3(A_t + A_s)(T_D - T_G)]$$

$$- h_4 A_s(T_D - T_S). \qquad (1)$$

Here, the extra unknown T_C (the temperature of the transparent cover) appears in addition to the other unknowns of part III of this paper. Hence, one more energy conservation relation for the transparent cover has been derived. This is written as

$$A_t[\sigma\epsilon_{\text{glass}}(T_C^4 - T_{\text{sky}}^4) + h_1(T_C - T_A)] = [\sigma(\epsilon T_D^4 - \epsilon_{\text{glass}} T_C^4) + h_5(T_D - T_C)] A_t, \qquad (2)$$

where the heat storage term $[(mC_p)_C(dT_{C/dt})]$ has been neglected.

These two equations (1) and (2), along with equations (2) and (4) of part III, have been solved simultaneously for the gas holder and slurry temperatures. The results are shown in figures 2 and 3.

After the computation of the temperatures, the heat losses from the gas holder and the slurry were also determined (table 1). In this modified type of biogas plant, the heat losses occurring from the top of the gas holder are reduced considerably, as may be seen clearly from table 1. In addition, if the water which is heated in the pond is removed at the time when it is near its maximum value, $(T_D)_{\text{max}}$, and used for mixing with the cattle dung to make up the daily charge for the biogas plant, this 'hot charging' will either completely eliminate the heat loss due to charging, or reduce it considerably depending on T_{ch} and $(T_D)_{\text{max}}$. In fact, by just 'hot charging' the biogas plant everyday, the slurry temperature can be increased as indicated in figure 3. This figure shows a staircase-like increase in slurry temperature assuming that the ambient conditions do not change during this period of temperature build-up.

If the higher slurry temperature achieved by this process is less than the optimum fermentation temperature of 35°C, and the intention is to operate the plant at 35°C, then additional heat must be supplied to the plant from external sources. But the magnitude of this additional heat is much less than if there had been no reduction of

*The nomenclature is the same as in part III of this paper

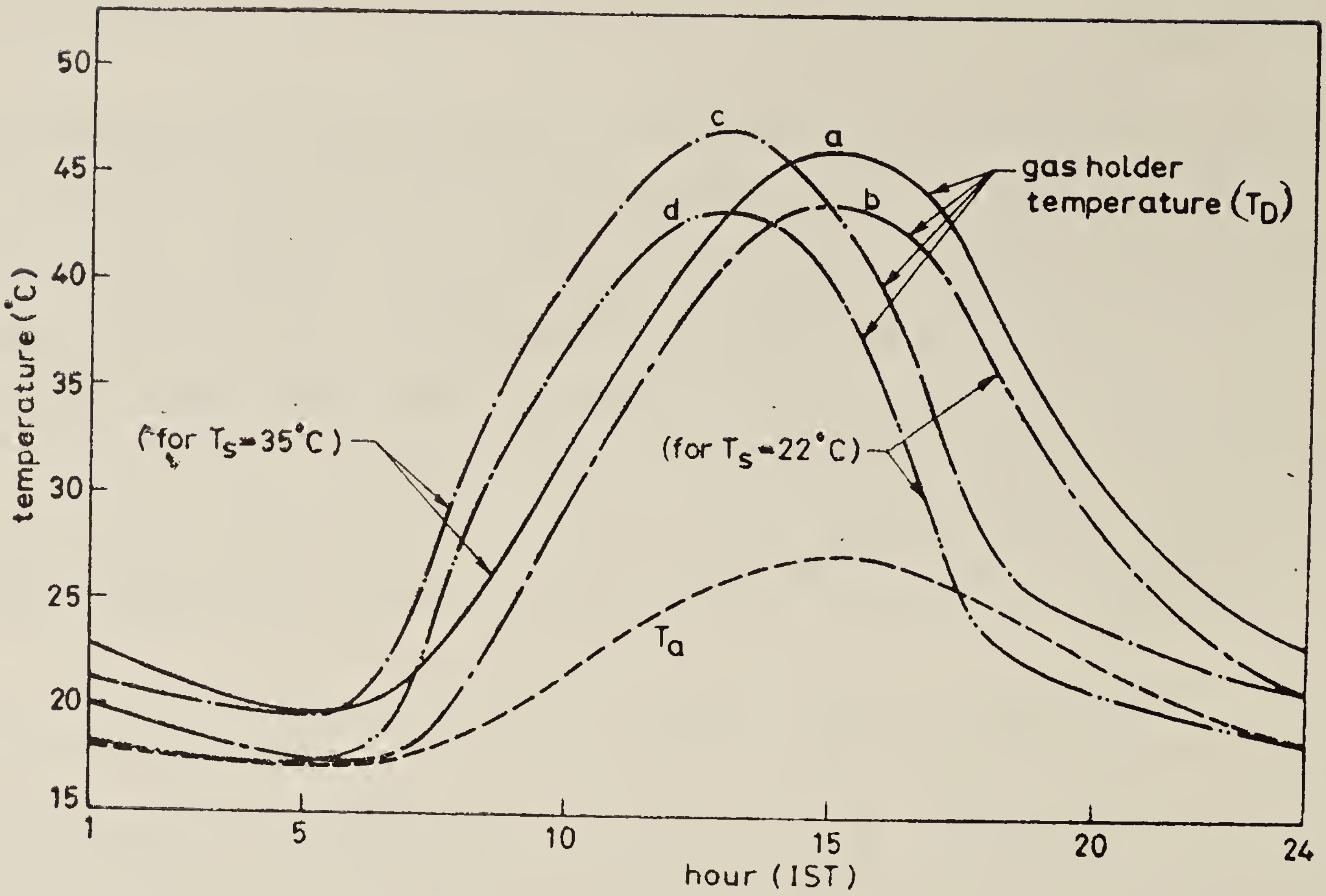

Figure 2. Temperature history of gas holder for
a. modified KIVC design (including solar water heater on top) with $T_s = 35°C$
b. modified design $T_s = 22°C$
c. conventional KVIC plant $T_s = 35°C$, and
d. conventional plant $T_s = 22°C$

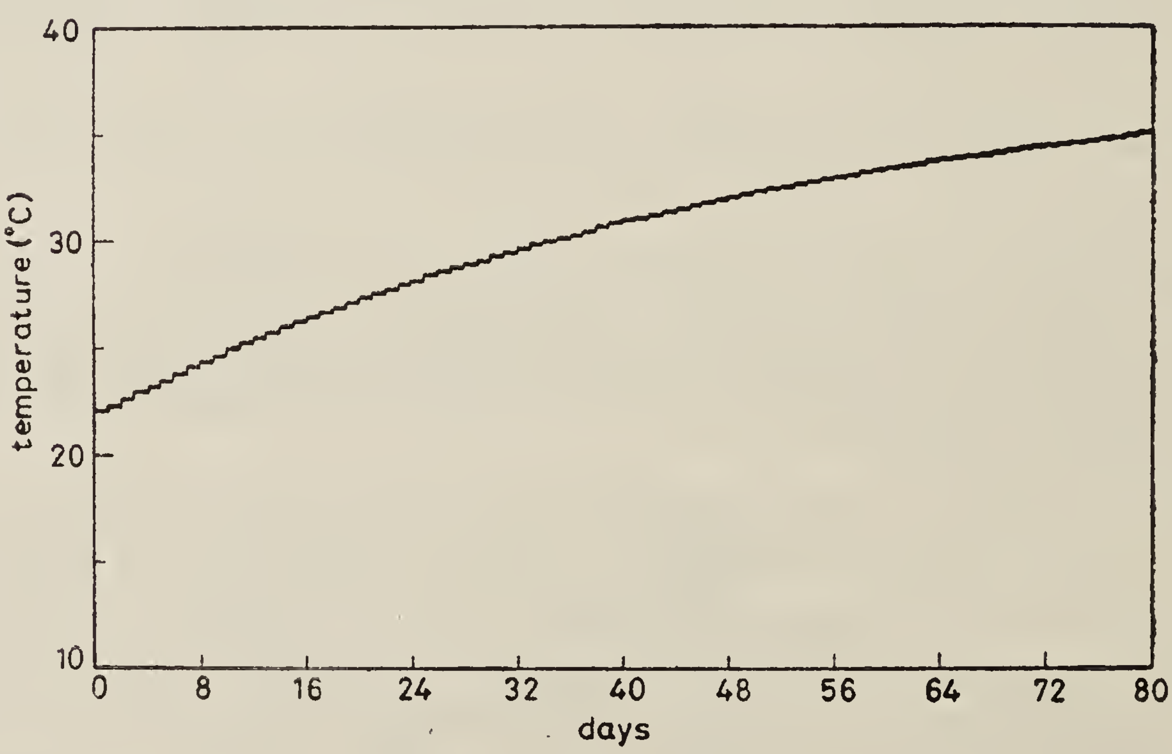

Figure 3. Increase in slurry temperature by addition of heated charge prepared by mixing solar heated water with dung.

heat losses from the gas holder roof and no ' hot charging '. The extent of saving in the heat to be supplied externally is shown in table 1.

4. Experimental results

The thermal analysis described above shows a clear-cut advantage in making a solar water-heater ' ride piggy-back ' on the floating gas holder of a biogas plant. It was therefore decided to test out the idea experimentally.

Table 1. Thermal behaviour of KVIC and ASTRA plants (Calculations are for January in Bangalore)

	KVIC design (5·66 m³/day)				ASTRA design (1·70 m³/day)	
	Conventional gas holder (slurry at 22°C)	Modified gas holder (slurry at 22°C)	Conventional gas holder (slurry at 35°C)	Modified gas holder (slurry at 35°C)	Conventional gas holder*	Modified as holder*
Diameter of the slurry pit (m)	1·95	1·95	1·95	1·95	1·75	1·75
Depth of the slurry pit (m)	4·80	4·80	4·80	4·80	1·50	1·50
Diameter of the gas holder (m)	1·83	1·83	1·83	1·83	1·68	1·68
Depth of the water on top of the gas holder (m)	—	0·10	—	0·10	—	0.05
Heat content of the slurry (kcal/°K)	14,340	14,340	14,340	14,340	3,656	3,656
Heat content of the gas holder (kcal/°K)	36·46	299·74	36·46	229·74	12·95	124
Heat loss/day from the gasholder (kcal) Top	10,065	4,006	11,252	5,256	8,593	3,381
Heat loss/day from the gasholder (kcal) Side	9,527	10,545	10,730	12,739	3,272	3,668
Heat loss from the slurry to the ground (kcal/day)	−957·75	−1,048	11,818	11,818	−280	−280
Net heat loss (kcal/day)	−18	−5,146	18,810	11,156†	−15	−4,391
Gas required to compensate net heat loss (cubic m/day)	—	—	3,48	2,07	—	—

†Excludes the charge cooling loss of 3660 kcal/day that column III has in addition
*Slurry at 22°C

The 1·70 m³/day biogas plant of ASTRA design described in part II of this paper was modified by extending the mild steel sides of the gas holder to 0·3 m above its roof, which was painted black. This water tank permits a 0·1 m deep water pond to be formed on the roof of the gas holder. The pond was covered with a polythene sheet. Continuous recording of the temperature of the water pond showed that the latter attained its maximum temperature around 1500 hr. Hence, at about this time, the solar-heated water from the pond (about 220 litres in comparison with the daily requirement of 50 litres of water for charging the plant) was emptied out and used for mixing with the input dung for ‘ hot charging ’ the biogas plant.

Though the work has just commenced, the results of two weeks of ‘hot charging’ have been encouraging (table 2). This preliminary work was unfortunately started during the rainy season when the skies were cloudy most of the day—thus, the average 1500 hr water pond temperatures during this period were only 45.1 $\pm$ 6·5°C as compared to the approximately 60°C attained in earlier months. Further, the average temperature of the ‘ hot ’ input was only 35·9$\pm$4·2°C. Despite these ‘worst case’ conditions, there was an improvement of 11 % in daily gas yield (without the aid of

Table 2. Performance of solar-heated plant*

	1·70 m^3/day biogas plant	
	Standard	Solar-heated
Daily gas yield (m^3/day)	1·93±0·38	2·14±0·27
Gas yield (cm^3/g fresh dung)	38·4±7·6	42·8±5·4
Improvement	—	10·9%
Distilled water yield (litres/day)	—	1·7±0·7

*During two weeks operation in June 1979.

external heating) compared to the yield from the same plant without the water pond and hot charging (table 2). It appears that considerable improvement can be expected when the atmospheric conditions for solar water heating become more conducive. Thus, the innovation described here is likely to lead to drastic reductions in the size, and therefore in capital cost, of biogas plants of a given capacity.

Two problems emerged with the presence of the water pond on the gas holder: the latter tended (a) to become too heavy and (b) to tilt to one side. In the former case, the biogas sometimes preferred to bubble through the gap between the gas holder and the digester rather than accumulate in the gas holder —this problem can be overcome by using a gas holder which is lighter to the extent of the weight of the water pond, i.e., either a thinner, and therefore cheaper, gauge of mild steel, or alternative material. The tilting tendency leads to a local rupture of the anaerobic seal and gas escape—this problem can be overcome by changing over from the central guide-post suspension of the gas holder to its movement along three vertical guide rails located at the perimeter of the digester rim.

The preliminary experiments, during which extensive condensation of water droplets on the inside of the plastic sheet was observed, have played an important role in suggesting yet another development. By fixing a tent-shaped aluminium frame to the rim of the gas holder, and attaching the transparent polythene cover to the inside of this tent rather than laying it flat over the gas holder, a solar still has been formed (figure 1). After attaining a sufficient size, the condensed water droplets run down the sloping sides of the polythene tent and fall into a channel from where the collected distilled water can be tapped off. During the two weeks of experiments, a daily yield of 1·7 ± 0·7 litres of distilled water was obtained corresponding to a daily yield of 0·8 litres/m^2 of water pond surface. It is obvious that this yield will increase with improvement in the solar insolation and in the seal between the plastic cover and the water tank. For instance, in the favourable month of May, the daily distilled water yield was about 4 litres/day.

The amounts of distilled water referred to here may appear trivial, but the benefits of a solar still (operating in conjunction with the solar water heater on top of the gas holder) must be seen in the perspective of a village-scale biogas plant. For example, by fabricating a solar still on top of a 1500 cubic ft/day (42·5 m^3/day) biogas plant, the distilled water yield would be anywhere between 20 to 80 litres/day, and this distilled water can be used for medical purposes, for bringing brackish water within potable limits, etc.

The incremental costs associated with the incorporation of the solar water heater and solar-still functions are marginal (under 10%) in comparison with the construction of separate devices to perform these tasks. This enormous cost reduction is a characteristic of spatially-integrated hybrid devices which perform more than one task. In this sense, the novel biogas plant incroporating a solar water heater and solar still is an excellent example of the principle of spatial task integration (Reddy & Subramanian 1979).

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The design of rural energy centres

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Abstract. Need-oriented, self-reliant and environmentally-sound development demands that the design of rural energy centres proceeds step-wises from energy consumption patterns to energy needs to technological options to selection of energy sources and devices to integration of these sources and devices into a system. The procedure is illustrated with Pura village as a concrete example. There is first a description of Pura's energy consumption pattern, and its energy needs and energy resources. In the absence of a rigorous methodology for solving the fundamental problem of designing rural energy centres, *viz.*, given the energy resources and requirements, what is the optimum way of harnessing *i* energy sources with the aid of *j* devices to achieve *k* energy-requiring tasks?, a heuristic approach based on second law efficiencies is used. The result is a design for a rural energy centre for Pura. The first phase of such a centre involves a community-scale biogas plant to meet the energy needs of cooking, domestic electric illumination, and pumping domestic water, in addition to providing organic fertiliser and producing rice husk ash cement. The Pura exercise is used to formulate several principles of rural energy system integration, *viz.*, mixing, cascading and combining of sources, spatial task integration and time-sharing. Finally, the general problem of designing rural energy centres is mathematically formulated. The formulation highlights important data gaps which must be filled before rigorous rural energy system designing can be achieved.

Keywords. Rural energy; village energy consumption; energy planning; rural energy centre; design methodology; second law efficiencies; community biogas plant; energy system integration.

1. Introduction

The growing realisation that the benefits of growth in developing countries have not ‘ trickled down ’ to the rural poor has stimulated global interest in technologies for rural development. In particular, problems of rural energy have attracted widespread attention. This attention has focussed on descriptions of the rural energy ‘ crisis ’ (Eckholm 1976), guesstimates of rural consumption patterns (Prasad *et al* 1974; Makhijani 1976; Revelle 1976; Reddy & Prasad 1977, Reddy 1978), the formation of centres/groups for village energy studies*, the organisation of seminars/ symposia on the subject**, and the design of technological packages for rural energy centres (Anon 1976).

The centre for the Application of Science and Technology to Rural Areas (ASTRA) too has been compelled, from its very inception, to interest itself in rural energy by the constant complaint of the villagers with whom it was in contact that ‘ fuel ’ was one of their most pressing problems. Several difficulties, however, came to the fore immediately. Firstly, there was hardly any information at all on energy

*For example at the Institute of Development Studies, Sussex.
**For example, the Royal Institution Forum, London, 20–22 June 1979.

consumption patterns now prevalent in villages—data was available on UK or USA, but not on villages a few kilometres from the Institute. Secondly, even if the information had been available, a proven methodology for rural energy planning was lacking.

Thus, in the villages in which it is working, ASTRA had to start from ' zero ', develop an energy data base and then formulate an energy strategy for implementation. Though ASTRA's work is just entering the implementation phase, its preliminary methodology for rural energy planning is being reported here to provoke scrutiny and refinement.

2. Basic approach

All attempts at external intervention in rural life are inspired, consciously or unconsciously, explicitly or implicitly, by a viewpoint on rural development. ASTRA's perspective (Reddy 1979) has been a rural development which is: (a) need-oriented (' starting from the needs of the neediest '), (b) self-reliant, and (c) environmentally sound.

Such a perspective demands that rural energy planning be based on an approach consisting of the following steps:

(i) elucidation of current rural energy consumption patterns;
(ii) translation of these patterns into a set of energy needs arranged according to priority;
(iii) consideration of the feasible technological options, including the traditional ones, of satisfying these energy needs with the available resources;
(iv) selection of the ' best ' option for satisfying each category of need;
(v) integration of the selected options into a system.

This approach has been used for the design of a rural energy centre for Pura village*, and will therefore be described with reference to this concrete case.

3. Pura's energy consumption pattern

With no precedent to follow, the methodology for ASTRA's survey of rural energy consumption patterns was evolved through a ' trial run ' in four villages, the lessons of which were used to make a detailed study of six villages including Pura. Whereas the ' trial run ' was based wholly on verbal responses to questions from a questionnaire, the detailed study was based, in addition, on observations and measurements.

Since Pura's energy consumption pattern is described in detail elsewhere (Ravindranath *et al* 1979), only those features essential for the design of a rural energy centre for the village are outlined below.

**Pura* (latitude: 12°49′00″ N, longitude: 76°57′49″ E, height above sea level: 670·6 m, average annual rainfall: 50 cm/year, population (in September 1977): 357, households: 56) is one of the villages in a cluster in Kunigal Taluk, Tumkur District, Karnataka State, South India, amidst which ASTRA has established an Extension Centre to generate a grass-roots understanding of rural problems through direct interaction with the people and to elicit their response to technological alternatives.

The energy-utilising activities in Pura are*: (a) agricultural operations (with ragi and rice as the main crops), (b) domestic activities, *viz.*, grazing of livestock, cooking, gathering firewood and fetching water for domestic use including drinking, (c) lighting and (iv) industry (pottery, flour mill and coffee shop). These activities are achieved with the following *direct* sources of energy: human beings, bullocks, firewood, kerosene and electricity.

An aggregated matrix showing how the various energy sources are distributed over the various energy-utilising activities is presented in table 1 in the units appropriate to the sources.

Notwithstanding the methodological and conceptual problems in converting the various sources to a common energy unit (e.g., kilocalories), there are three advantages in doing so: (i) an idea can be obtained of the relative contributions of the various sources to the total energy consumption (ii) a summation over all sources contributing to a particular activity leads to the total magnitude of energy it now utilises (iii) the total magnitudes of energy for the various activities facilitates a ranking of these magnitudes. Using the following conversion factors: 250 kcal/man hour, 200 kcal/woman hour, 120 kcal/child hour, 2300 kcal/bullock hour, 3800 kcal/kg firewood**, 860·4 kcal/kWh electricity, and 8980 kcal/litre kerosene, a source-activity matrix for Pura village has been obtained (table 2).

The matrix yields the following ranking of sources (in order of percentage of annual requirement): (a) fire wood 89% (b) human energy 7% (c) kerosene 2% (d) bullock energy 1% (e) electricity 1%. The ranking of activities is as follows: (a) domestic activities 91% (b) industry 4% (c) agriculture 3% (d) lighting 2%.

Human energy is distributed thus: domestic activities 80% (grazing livestock 37%, cooking 19%, gathering firewood 14%, fetching water 10%), agriculture 12%, and industry 8%. Bullock energy is used wholly for agriculture including transport. Firewood is used to the extent of 96% (cooking 82% and heating bath water 14%) in the domestic sector, and 4% in industry. Kerosene is used predominantly for

Table 1. Energy sources and activities in Pura

	Agriculture	Domestic	Lighting	Industry	Total
Human hours	34848	255506	—	20730	311084
(Man hours)	(19914)	(82376)	—	(16485)	(118775)
(Woman hours)	(14934)	(113928)	—	(4245)	133107
(Child hours)	—	(59202)	—	—	(59202)
Bullock hours	5392	—	—	—	5392
Firewood (kgs)	—	207807	—	8930	216737
Kerosene (litres)	—	—	1938	156	2094
Electricity (kWh)	7264	—	3078	820	11162

*Transport has been included in agriculture because the only vehicles in Pura are bullock carts and these are used almost solely for agriculture-related activities such as carrying manure from backyard compost pits to the farms and produce from farms to households.

**Based on specimen collection by H I Somashekar and bomb-calorimetry by P Rajabapaiah.

Table 2. Pura energy source-activity matrix (× 10^6 kcals/year)

	Agriculture	Domestic	Lighting	Industry	Total
Human	7·97	50·78	—	4·97	63·72
(Man)	(4·98)	(20·59)	—	(4·12)	(29·69)
(Woman)	(2·99)	(22·79)	—	(0·85)	(26·63)
(Child)	—	(7·40)	—	—	(7·40)
Bullock	12·40	—	—	—	12·40
Firewood	—	789·66	—	33·93	823·59
Kerosene	—	—	17·40	1·40	18·80
Electricity	6·25	—	2·65	0·71	9·61
Total	26·62	840·44	20·05	41·01	928·12

Total energy = 928 × 10^6 kcal/year; = 1·079 × 10^6 kWht/year; = 2955 kWht/day; = 8·28 kWht/day/capita

lighting (93%), and to a small extent in industry (7%). Electricity flows to agriculture (65%), lighting (28%) and industry (7%).

There are several features of the pattern of energy consumption in Pura which must be highlighted.

(i) What is conventionally referred to as *commercial* energy, i.e., kerosene and electricity in the case of Pura, accounts for a mere 3% of the inanimate energy used in the village, the remaining 97% coming from firewood.* Further, notwithstanding recent doubts (Rudolph & Lenth 1978), firewood must be viewed as a *non-commercial* source since only about 4% of the total firewood requirement of Pura is purchased as a commodity, the remainder being gathered at zero private cost.

(ii) *Animate* sources, *viz.*, human beings and bullocks, only account for about 8% of the total energy, but the real significance of this contribution is revealed by the fact that these animate sources represent 77% of the energy used in Pura's agriculture. In fact, this percentage would have been much higher were it not for the operation of *four* electrical pumpsets in Pura which account for 23% of the total agricultural energy.

(iii) Virtually all of Pura's energy consumption comes from traditional renewable sources—thus agriculture is largely based on human beings and bullocks, and domestic cooking (which utilises about 80% of the total inanimate energy) is based entirely on firewood**.

(iv) However, the environmental soundness of this pattern of dependence on renewable resources is achieved at an exhorbitant price: levels of agricultural productivity are very low, and large amounts of human energy are spent on firewood gathering

*Pura uses about 217 tonnes of firewood per year, i.e., about 0·6 tonnes/day for the village, or 0·6 tonnes/year/capita.

**Unlike some rural areas of India, dung cakes are *not* used as cooking fuel in the Pura region. In situations where agro-wastes (e.g., coconut husk) are *not* abundant, it appears that, if firewood is available within some convenient range (determined by the capacity of head-load transportation), dung cakes are never burnt as fuel; instead dung is used as manure.

(on the average, about 2·6 hr and 4·8 km per day per family to collect about 10 kg of firewood).

(v) Fetching water for domestic consumption also utilises a great deal of human energy (an average of 1·5 hr and 1·6 km per day per household) to achieve an extremely low *per capita* water consumption of 17 litres per day.

(vi) 46 % of the human energy is spent on grazing livestock (5·8 hr/day/household) which is a crucial source of supplementary household income.

(vii) Children contribute a crucial 30 %, 20 % and 34 % of the labour for gathering firewood, fetching water and grazing livestock respectively. Their labour contributions are vital to the survival of families, a point often ignored by population and education planners.

(viii) Only 25 % of the houses in the 'electrified' village of Pura have acquired domestic connections for electric lighting, the remaining 75 % of the houses depend on kerosene lamps, and of these lamps, 78 % are of the open-wick type.

(ix) A very small amount of electricity, *viz.*, 30 kWh/day, flows into Pura, and even this is distributed in a highly inegalitarian way—65 % of this electricity goes to to the 4 irrigation pumpsets of 3 landowners, 28 % to illuminate 14 out of 56 houses, and the remaining 7 % for one flour-mill owner.

4. Pura's energy needs

The above pattern of energy consumption constitutes the data base for formulating an energy plan for Pura. This objective is facilitated by representing energy consumption in terms of end-uses or tasks classified with a physics perspective, rather than activities with socio-economic significance. It is also convenient to separate the end-uses of inanimate and animal energy from those of human energy—whereas the former permit the selection of sources and devices appropriate to the energy-utilising tasks, the latter enable a consideration of alternative systems that will improve the quality of life by alleviating or eliminating drudgery. Such an end-use analysis for Pura is shown in table 3, which also contains the output energies taking into account the efficiencies of energy utilisation.

In the first part of the table, the end-uses of inanimate and animal energy (along with indicative temperatures corresponding to these tasks) are ranked in order of decreasing magnitude of energy utilised. This ranking according to magnitude may be considered to provide an *initial* list of priorities for energy planning. For the list to promote development, end-uses which involve satisfaction of the needs of the neediest or the majority can be given an extra weight, e.g., lighting which all homes require can be given a higher weight than power for private pumpsets.

Such an approach leads to the identification of the energy requirement of cooking, i.e., medium-temperature heating (95–250°C), as the first priority in rural energy planning. Unfortunately, this is one requirement which is totally ignored in virtually all current thinking—for example, rural electrification which is being promoted as the answer to rural energy problems does not envisage meeting cooking energy needs even in a remote future.

Once important urgent priorities are met, other items must move up the list. That is, the priority list must change with time. In such a dynamic perspective, end-uses relating to crop production, e.g., water lifting and mobile power for ploughing, to

Table 3. End-uses of energy in Pura
Inanimate and animal energy

	End-use	Input energy/year (kcal/10^6)	Efficiency*	Output energy/year (kcal $\times 10^6$)
1.	Heating (95–250°C)	688·9	5	34·4
2.	Heating (~55°C)	112·4	5	5·6
3.	Heating (~800°C)	23·8	5	1·2
4.	Lighting	20·1	2·5	0·5
4.1.	Lighting (electrical)	(2·7)	10	(0·3)
4.2.	Lighting (kerosene)	(17·4)	1	(0·2)
5.	Mobile power	12·4	20	2·5
6.	Stationary power	7·0	80	5·6
6.1	Water lifting	(6·3)	80	(5·0)
6.2	Flour milling	(0·7)	80	(0·6)
	Total	864·6		49·8

*Estimates

Human energy

	Human activtiy	Human energy expenditure		
		Hours/year	Hours/day/ household	kcal year $\times 10^6$
1.	Domestic	255,506	12·5	50·8
1.1	Livestock grazing	(117,534)	(5·7)	(23·4)
1.2	Cooking	(58,766)	(2·9)	(11·7)
1.3	Firewood gathering	(45,991)	(2·3)	(9·1)
1.4	Fetching water	(33,215)	(1·6)	6·6
2.	Agriculture	34,848	1·7	8·0
3.	Industry	20,730	1·0	5·0
	Total	311,084	15·2	63·8

post-harvest operations, and to village industries should quickly take high priority.

The second part of table 3 represents the end-uses of human energy in Pura. It is obvious that the inhabitants of Pura suffer burdens which have been largely eliminated in urban settings by the deployment of inanimate energy. For example, gathering firewood and fetching water can be eliminated by the supply of cooking fuel and water respectively. Thus, energy planning for Pura must scrutinise the expenditures of human energy to see whether they involve necessary employment, meaningful work or avoidable drudgery. This exercise will lead to important additional priorities in an energy plan for Pura. These priorities must include the supply of cooking fuel to Pura's homes, the provision of a convenient water supply, and the production of

fodder and feed for livestock. Unfortunately, improvements in the quality of life through an alteration in the pattern of expenditure of human energy rarely form part of the agenda of rural energy planning. However, great caution must be exercised with regard to human energy in agriculture and industry to ensure that inanimate energy inputs do not aggravate the human condition, for example, by increasing total unemployment.

5. Pura's energy resources

Pura's energy resource position must next be examined. Pura, like most Indian villages, has no fossil fuel resources. Even if it had, the use of irreplaceable fossil fuels for energy is debatable. Pura's only internal energy sources are those arising directly, or indirectly, from photosynthesis. Though, in principle, all biomass can be harnessed for energy purposes (if necessary, after suitable processing), the materials which are immediately usable in Pura are firewood, crop wastes (e.g., rice husk) and animal wastes.

The present pattern of firewood usage is unsustainable for more than a few years—firewood is a rapidly dwindling resource. For firewood to become a dependable resource (instead of a liability), it must be harvested from efficiently managed ' energy forests ' where fast-growing trees are grown specifically for their firewood output. In such an alternative pattern of firewood usage, the resource position depends upon the particular species that are grown, and of course on the land made available for the energy forest. A yield of about 50 tonnes of dry wood per hectare per year can be assumed for species such as *Casuarina* or *Leucaena leucocephala* (Seshadri 1978). Thus, about 5 hectares will yield Pura's present firewood consumption of 217 tonnes per year. The firewood from an energy forest can either be used directly or after conversion to charcoal or methanol. Notwithstanding these attractive features, energy forests are associated with long gestation times of 3–5 years, and cannot therefore be part of an immediate solution.

In perhaps the same category is ethanol production which can be established in a few years. One hectare of land yields annually about 100 tonnes of sugarcane and therefore 4·4 tonnes of molasses from which about 870 litres of ethyl alcohol fuel can be obtained (Prasad *et al* 1979).

One important difference between fuel-wood forests and ethanol from sugarcane plantations is that the latter requires ' good ' agricultural land suitable for foodgrain production, in contrast to the former which can make do with non-arable land. Thus, the development of these two types of fuel resources must be part of an optimum land-use planning. In so far as the land under forest cover is far below the 30% declared as optimum, the development of energy forests should perhaps be preferred.

In contrast to the relatively long gestation times associated with the growth of energy forests and the development of ethanol production, animal wastes are a major resource which can be tapped within a year. The energy survey indicated that Pura's cattle population of 143 yields about 1·02 tonnes of wet dung per day from overnight droppings alone.* This minimum of 370 tonnes of wet dung per year is basically a cellulosic material which can be anaerobically fermented in a biogas plant to yield at

*Based on weight measurements made in the houses at dawn.

least* 35 m^3 per day or 12,775 m^3 per year of biogas (60–70 % CH_4 and 30–40 % CO_2) with a calorific value of 5340–6230 kcal/m^3.

The two renewable energy inputs flowing into Pura spontaneously are solar and wind energy. Measurements of solar insolation at Pura have not been made, but the data from Bangalore indicates an average solar power of about 0·8 kW/m^2. Of course, the diffuse character of solar energy, and its restriction to about one-third of a day are well-known. Wind data have been obtained at the ASTRA Extension Centre, about 2 km from Pura. Though the average wind speed is about 15 km/hour, it can go as high as 30–40 km/hour for 1–2 hr intervals. But, there is a marked seasonality in the wind, with about 80% of the annual wind energy of about 6000 kWh/hectare being available in about four months of the year (Shrinivasa *et al* 1978).

Electricity and kerosene are both energy sources which are imported into Pura. At present, Pura consumes an average of 30 kWh/day of electricity. This low figure is primarily because the present demand is from the relatively rich of Pura who are very few in number—only 25% of the homes have electric lights and a mere 5% own irrigation pumpsets. But, even if this demand were to increase markedly, there are major difficulties in making the supply from the grid keep pace. Firstly, the growth of electricity generation has fallen far short of the rise of nation-wide demand, even though the rural share is less than 20%. Secondly, increasing the capacity of lines to villages implies increased transmission and distribution costs which are already above Rs. 3000/kW. These constraints on generation and transmission mean that grid electricity must be viewed as a *limited* resource even if the generation is from renewable sources, e.g., hydel generation.

The situation is quite similar with kerosene. 40% of the country's 3·4 million tonnes consumption in 1977-78 was imported from abroad, and domestic lighting accounts for almost 60% of the total consumption (Shah 1979). With jet aircraft being strong competitors for the supply, it is clear that Pura cannot count on imported kerosene as an energy resource for long, i.e., Pura must find a substitute for kerosene as rapidly as possible.

6. Selection of sources and technologies to meet Pura's energy needs

The fundamental problem of rural energy planning, and of the design of rural energy centres, can be stated thus: given the energy resources and requirements, what is the optimum way of harnessing i energy sources with the aid of j devices to achieve k energy-requiring tasks subject to l constraints? In other words, if ijk is designated as an *energy path* by which a source i is utilised with the aid of a device j to fulfil an energy task k, what is the optimum set of energy paths, and the optimum energy flow along each one of this set, to meet the energy needs with the available resources? An immediate solution is required to meet present needs, but it is also essential to anticipate change, and to develop solutions which cater to the contours of future needs.

A rigorous methodology for solving the fundamental problem posed above has yet to be developed. Pending such an achievement, a heuristic approach has been adopted for Pura's energy needs.

*The figures are based on the performance of the unheated biogas plant at the Institute (Rajabapaiah *et al* 1979).

In the case of Pura, the energy-requiring tasks have been listed in table 3, from which it may be seen that $k = 6$, *viz.*, medium-temperature heating (95–250°C), low-temperature heating (~55°C), lighting (~2000°C), stationary power, mobile power and high-temperature heating (~800°C). The inanimate energy sources available in Pura now or in the very near future are: energy forests, ethanol, biogas, solar energy, wind energy, grid electricity and kerosene; i.e., $i = 7$. Despite the limited number of tasks and of sources, a very large number of energy paths can be considered while going from sources to tasks. Even excluding multiple paths between particular sources and particular tasks (e.g., biogas → mantle lamp, and biogas engine → generator → electric bulb), the number of conceivable paths can be as many as 42 in the Pura case.

In this context, guidance can be sought from the second law of thermodynamics, and in particular, the concept of second law efficiencies. This concept has been elaborately discussed in a report sponsored by the American Physical Society (Anon 1975), and therefore, only its important implications will be cited here:

(i) Every energy source must be associated with a grade or quality, which may be determined by its temperature or the temperature it can produce. Low temperature heat is the lowest grade (or quality) energy, electrical and mechanical energy (which correspond to infinite temperatures) are the highest quality energy, and chemical fuels (coal, oil, biogas) come in between.

(ii) The second law efficiency is the ratio of the actual useful work/heat transferred with a given source and device to the *maximum* possible work/heat transferable by *any* source and device for the same task. Thus, the second-law efficiency sets up an ideal or norm for a particular task k. It permits a screening of various energy paths ijk for the achievement of that task k, and the selection of the path with the highest second-law efficiency. Whereas the first-law efficiency, which is the ratio of the actual useful work/heat output of a given source and device in the performance of the task to the energy input, reveals how well the *given* source and device is performing, the second law efficiency shows which (of a number of alternative sources and devices) is the best source and device for achieving the task.

(iii) For a given task, it is the maximisation of second law efficiencies that determines the minimisation of fuel consumption in the case of consumable fuels, and of capital costs in the case of renewable sources.

(iv) The maximisation of second law efficiencies implies that sources and devices must be *matched* to the task. This matching is facilitated by two thumb-rules: (a) ‘ Do not use a higher quality source than the task deserves!’, and (b) ‘ For the matched source, choose the device which transfers the most useful work/heat!’

Thus, second law efficiencies are a powerful heuristic for selecting the technically ‘ best ’ energy technologies (sources and devices) for the various tasks that need to be performed. Unfortunately, the values of second-law efficiencies have not been tabulated for all paths ijk to various tasks k. In the case of paths for which second-law efficiencies are not available, a programme of determining them must be

launched.† Pending the establishment of a complete table of second-law efficiencies, the thumb rules can be used.

Table 4. Selection of sources and devices for Pura.

task	alternatives
(1) medium-temperature heating	sources → devices biogas → gas burner energy forests → wood/charcoal stoves
(2) low-temperature heating	waste heat → wood/charcoal stoves solar → solar water-heater/solar dryer
(3) lighting	electricity → incandescent lamps, fluorescent tubes
(4) stationary power	draught animals → animal-powered devices human labour → pedal-powered devices wind → wind mills biogas → biogas engine energy forests → producer-gas engine ethanol → internal combustion engine electricity → electric motor
(5) mobile power	draught animals → animal-powered devices human labour → pedal-powered devices ethanol → internal combustion engine energy forests → producer-gas engine biogas → biogas engine
(6) high-temperature heating	biogas → furnace charcoal → furnace

* The sources and devices within boxes correspond to those proposed for phase I of rural energy centre for Pura.

†For example, it can be shown that the second law efficiency for raising water from room temperature up to boiling point (a process which accounts for about two-thirds of Pura's energy requirement for cooking rice) by burning biogas fuel is double the second-law efficiency when an electrical immersion heater is used. This factor of 2 is for *thermally* produced electricity.

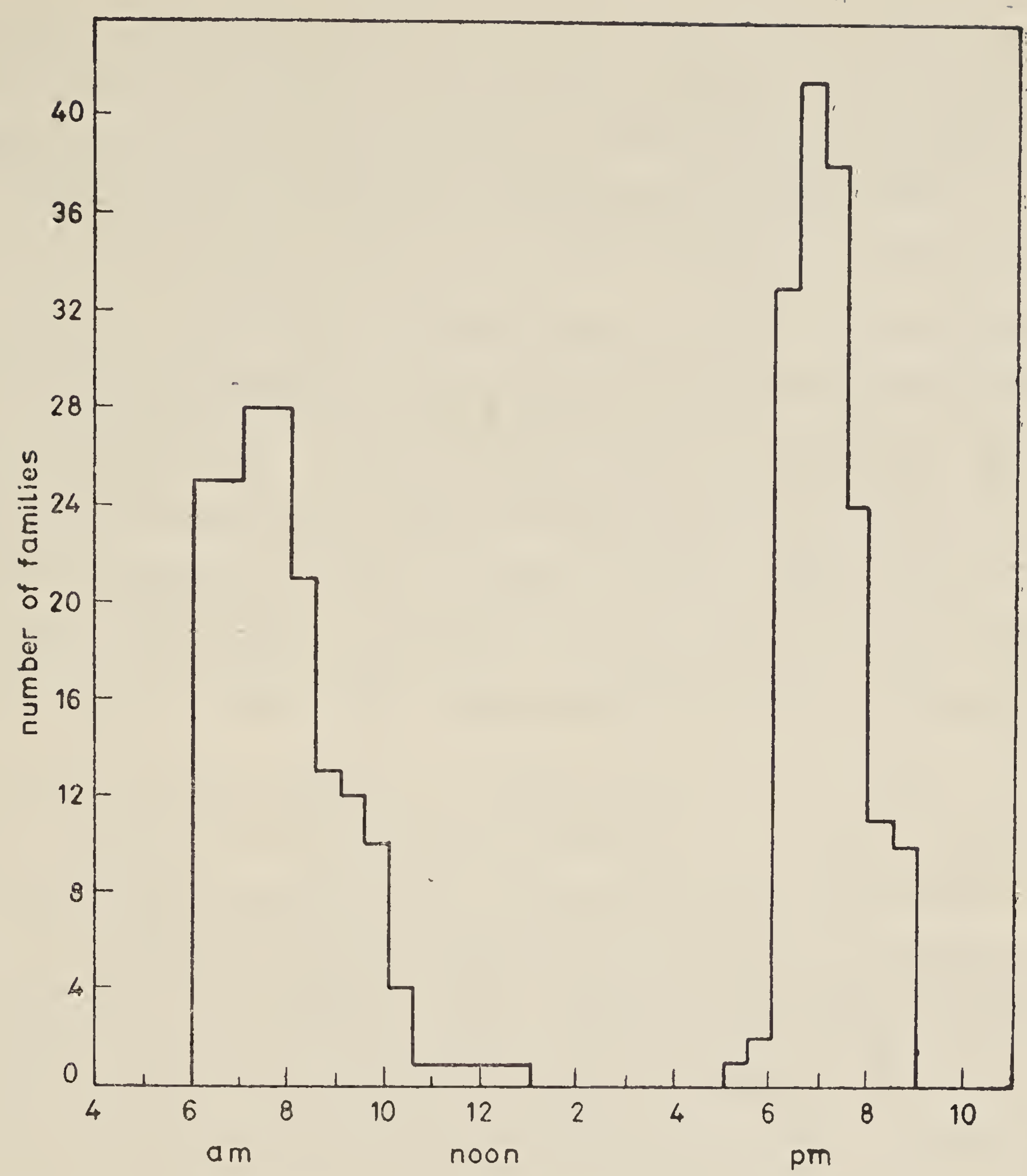

Figure 1. Cooking hours in Pura

The use of the thumb rules leads in the case of Pura to the selection of a very limited set of energy paths, i.e., sources and devices to achieve the tasks corresponding to the energy needs of Pura (table 4).

To restrict the alternatives further, additional constraints must be imposed.

The first additional constraint is the necessity of matching the time-dependence of the energy-utilising task (the load curve for the task) with the time-variation, if any, of the supply of energy from the chosen source. If energy from this source is not available when it is needed, then storage of energy becomes imperative. But, storage implies a new path *ij'k* different from *ijk* in the absence of storage, and therefore a new second-law efficiency which may not be as high.

Cooking with solar energy is an excellent illustration of the point under discussion. Figure 1 shows clearly that Pura families cook during those hours when the sun is not shining strongly. Hence, for solar cookers to be useful, either these families must change their cooking hours, and therefore living patterns, or solar energy must be stored. The former option may result in women losing employment, and the latter requires expensive storage systems.

Wind energy must also be examined from the point of view of whether the water-lifting needs of agriculture occur during the months of May to September when the winds are strongest. Superficial observation indicates that the maximum water-lifting needs are during these pre-monsoon windy months, but much more in-depth study is required of both cropping and wind patterns.

The second additional constraint concerns the development criterion of self-reliance. Imports of energy into the village can be ruled out in the first iteration, and permitted only when it is found that internal energy sources and those coming into the system ' free ' (solar, wind, flowing water) cannot meet the energy needs. In other words, local resources must be chosen, unless they are inadequate to satisfy the needs.

The third additional constraint arises from the development criterion of environmental soundness. To sustain development over the long run, renewable sources of energy mu st be chosen. Hence, depletable sources (fossil fuels) must be excluded.

The fourth additional constraint is that of *power*. This constraint becomes relevant whenever a task k must be completed within a certain time t_k, e.g., ploughing or harvesting or grain drying. Then, if the task requires the expenditure of energy E_k, its power requirement is $P_k = E_k/t_k$. This means that all paths involving sources i and devices j which deliver *less* power than is required for the task, i.e., $P_{ijk} < P_k$, are unacceptable; only those which satisfy the condition* $P_{ijk} \geqslant P_k$, can fulfil the task**.

The fifth additional constraint is that of availability of the technologies. Some energy paths (sources and devices for tasks) may be very attractive, but unavailable right now. Hence, immediate choices must be tentative, and when attractive options appear ' on the shelf ', they can be incorporated into the solution later.

The additional constraints described above narrow down the choice drastically. In the case of Pura***, the choice gets restricted to: (i) biogas and biogas burners for medium-temperature heating, (ii) electricity and incandescent lamps (or fluorescent tubes) for lighting, (iii) wind (whenever available) and windmills for stationary power (particularly water-lifting), (iv) biogas and biogas engines for stationary power (including water-lifting at sites close to biogas plant). In the case of low-temperature heating, mobile power, high-temperature heating and water-lifting for agriculture at sites which are not convenient either for wind or biogas energy, further technology development and/or analysis is required before definite choices are made to replace or supplement currently used sources and devices.

With regard to those energy-utilising tasks in Pura which now involve expenditures of human energy (table 3), gathering firewood and fetching water are directly related to cooking fuel and water supply respectively. Hence, by meeting the energy needs of medium-temperature heating and stationary power for domestic water-lifting, the expenditure of human energy on gathering firewood and fetching water can be wholly or partly reduced. The activity of free grazing of livestock is associated with the problem of fodder which must be solved in association with the fuel problem through two-tier *fodder-cum-fuel* forests. The question of human energy in agriculture and industry is part of the larger issue of employment generation and productivity increase and involves major socio-economic considerations which will not be dealt with here.

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*In fact, P_k may be a range of values. Further, the choice may not be a yes-no matter, and if $P_{ijk} < P_k$, the path ijk may still be used, but penalties will be paid, e.g., by way of decreased efficiency or output.

**This distinction between energy and power is often completely ignored in discussions on animal energy.

***Detailed consideration of the choice of technologies for each of the energy-utilising tasks in Pura is contained in a report of the Karnataka State Council for Science and Technology (Reddy *et al* 1979).

7. A rural energy centre for Pura

Notwithstanding the technical attractiveness of establishing a complete rural energy centre as a ' one-shot affair ', there is an important sociological reason why technological innovations must be introduced a few at a time and not all at once. Each innovation constitutes a perturbation imposed upon the village system which is forced to go into a transient response before settling down to a new state of equilibrium. It is the finite relaxation time of the village system which demands that new innovations be introduced only after the system has recovered from the previous ones. In other words, because the technology sub-system must fit into the larger socio-economic and cultural system of the village, it follows that a rural energy centre must *grow* in a phased manner; it must not be externally imposed as one massive perturbation which throws the village system into an instability from which it can save itself only by rejecting altogether the technological ' fix '. The phased growth of a rural energy centre also facilitates the mid-phase and inter-phase modifications of total system design which are certain to become necessary because of inadequate *a priori* understanding of villages and/or complex energy systems.

With this perspective, a community biogas system is envisaged as Phase I of the proposed rural energy centre for Pura. Biogas has been the first choice because it addresses itself to the first priority energy task in Pura, *viz.*, medium-temperature heating (95–250°C) for cooking. Further, individual family-size plants have been rejected for three reasons: (a) Only about 71% of Pura's families own cattle and therefore have the raw material for biogas plants. (2) Even if all the families have cattle, only a few can afford biogas plants—roughly the same number (i.e., three) as now own pumpsets, because family-size biogas plants are about 60–80% of the cost of pumpsets. (3) Biogas plants show clear-cut economies of scale—a community-size plant for 56 families is only 6·3 times the cost of a plant for one family.

The utilisation of the output of the community biogas plant is shown in figure 2. The design of the system has been guided by the fact that, even assuming a minimum yield of 0·034 m^3/kg fresh dung, a 42·5 m^3/day plant can provide a *surplus* of 11 m^3/day of biogas after meeting all the cooking energy needs of all the households in Pura. This means that the surplus gas must be utilised to yield economic returns which can completely subsidise the ' free supply ' of non-metered piped biogas to all the houses between fixed hours determined from present cooking patterns (figure 1).

It is proposed that the excess gas will be used to run a 5 HP biogas engine, and that the $5\frac{1}{2}$ hr engine time will (a) pump the daily water requirements of the biogas plant, and thereafter, the domestic needs of the village—20 min; (b) drive a generator to supply electricity between fixed hours—3 hr/day—to illuminate the non-electrified houses*; (c) provide motive power for a ball mill to grind for 2 hr/day rice husk ash (a waste product) and lime and produce saleable cement.

In addition, the plant will yield every day 1960 kg of liquid slurry which dries out with a nitrogen content of 1·9% which is double the nitrogen content of fresh dung dried in the open air.

Thus, in the first phase, it is proposed to: (a) pipe cooking fuel to all the homes in Pura, (b) provide electric lighting to the presently non-electrified homes and (c) pump

*This electricity will be charged for at the usual electricity board rates. Despite this, the households will have to spend only about 60% of what they now spend on kerosene lamps.

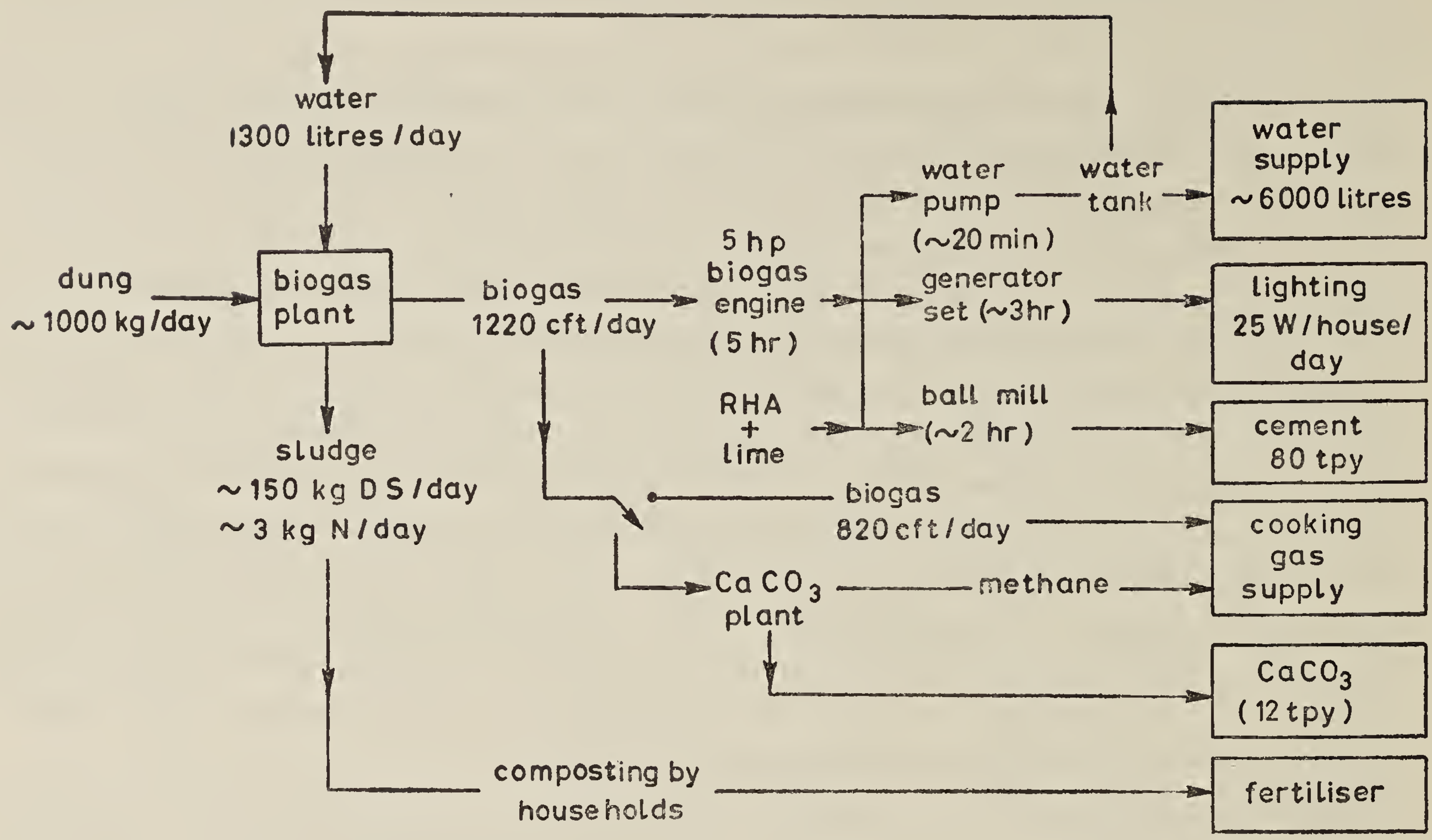

Figure 2. Community plant for Pura village

the domestic water requirements of the village to an overhead storage tank. In this process, the drudgery of firewood gathering for cooking fuel needs will be eliminated completely, and that of obtaining water will be alleviated.

The feasibility report (Reddy *et al* 1979) discusses in detail the commercial viability and social costs and benefits of this first phase of the rural energy centre for Pura. In brief, the capital cost of the entire Phase I system, i.e., biogas plant, gas distribution, biogas engine, generator, electricity distribution, pumpset, overhead water storage tank, ball mill for cement production, building and miscellaneous items, will be about Rs. 70,000. On this investment, the revenues on electricity and cement are envisaged to bring a return of 22% corresponding to an undiscounted pay-back period of 4·5 years.

The subsequent phases of the rural energy centre for Pura are being considered. Phase II may attempt to meet the total energy needs for low-temperature heating (of water for bathing) and partial needs of water lifting with windmills. In addition, the initiation of an energy forest will be considered. Phase III will seek to address itself to motive power needs perhaps through biogas, producer-gas and/or ethanol engines. However, far more analysis and hardware development is necessary before the designs of the subsequent phases are ‘ frozen ’.

8. Integration of sources and devices into a system

The heuristic design of a rural energy centre for Pura has revealed a few general principles for the integration of energy sources and devices into a system for achieving the required tasks. Since such principles have not been stated hitherto, a brief attempt is made here to indicate them.

The maximisation of second-law efficiencies requires the deployment of low-grade energy sources for low-grade tasks, and high-grade sources for high-grade tasks. So,

as long as there are several grades of tasks to be performed, it follows that energy sources of different grades should be used. Hence, system integration must involve the *principle of mixing sources to match tasks*—in general*, an optimised rural energy system should be based on a *mix* of energy sources *i*, where the *i*s refer to the sources energising the set of devices that accomplish the required tasks. These sources *i* may be *primary* in the sense that they are inputs to the system (e.g., solar or wind energy), or they may be *intermediate* sources which are produced inside the system from primary sources (e.g., electricity from wind energy) or from other intermediate sources (e.g., exhaust heat from an engine driven by producer gas obtained from firewood).

One possibility is a mix in which all the energy sources *i* are primary sources. If, in addition, all the devices are of the single-source single-task category, then the result is a system with virtually no element of integration. The system is simply a juxtaposition of separate sources, devices and tasks. Such a system can be represented by the network in figure 3a, from which it can be seen that the paths from sources through devices to tasks are quite separate and unconnected.

But, there are other possibilities. For instance, during the course of performing a task, a device can produce as ' waste ' a lower grade of energy than that which drives the device. The use of this waste energy to drive another device which performs a lower-grade task (figure 3b) illustrates *the principle of cascading*, according to which, ' as energy passes from a high-quality form to its impotent final form as ambient-temperature heat ' (Anon 1975), it performs a series of tasks of lower and lower grade. For example, one can think of a series of heat engines each one running on the waste heat from the previous one. A common example is where the waste heat from an engine is used to carry out a heating task, e.g., heating water.

Another approach to integration involves *the principle of combining energy sources* according to which two or more energy sources act in conjunction to perform a task (figure 3c). Thus, two energy sources can supplement each other's contribution in heating a fluid, e.g., solar pre-heated water can be used for cooking rice with biogas fuel. The merit of this principle of integration is that the higher grade energy only needs to complete the task which is partially accomplished by the lower grade energy.

The two principles of cascading and of combining energy sources can be used simultaneously. This requires the ' waste ' energy from one device, i.e., an intermediate source, being used to supplement the efforts of another energy source in another device, or even the same device (figure 3d). For example, exhaust heat from an engine can be used as a supplementary heat source along with a fuel; or the waste heat from a sugar-cane juice evaporator using bagasse fuel can be used to preheat the juice.

Instead of introducing integration at the source-end of devices, the integration can also be carried at the task-end.

This *principle of spatial task integration* is displayed by hybrid devices which perform more than one task (figure 3e). For example, when the roof of a biogas plant gas holder is made to serve as the absorber of a solar water-heater, the result is a hybrid multi-task device, *viz.*, biogas plant-cum-solar water-heater. In fact, the integral nature of the design can be extended one step further by providing a slope to the transparent greenhouse roof of the solar water heater ' riding piggy-back ' on the

*The special case is the rare type of system which has only one task to perform,

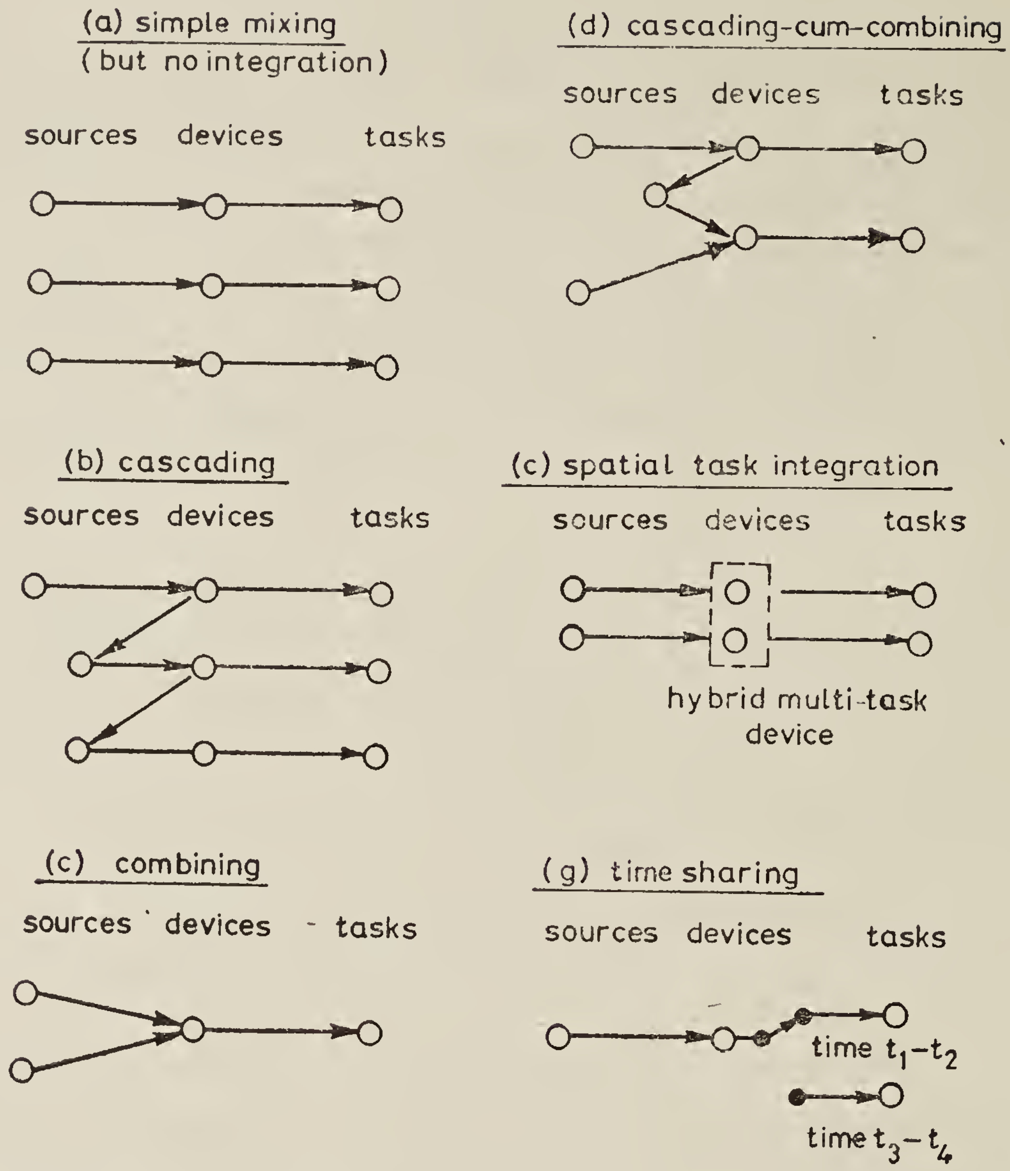

Figure 3. Principles of integration

biogas plant and by collecting the solar-distilled water from a gutter built into the side of solar water-heater (Reddy *et al* 1979).

Spatial integration of tasks in hybrid devices is not the only possibility; the *principle of time-sharing of devices* also represents a form of integration (figure 3f). For example, an engine or motor can be shared between tasks which required to be performed at different times, or a supply pipeline can be time-shared between biogas for cooking and water for domestic consumption (Reddy 1976).

These principles of assembling sources and devices into an energy system may prove useful in preventing current attempts to impose upon the village scene packages of hardware items which are not really integrated in the sense described above. The caution is against juxtaposing gadgets which have not been specifically designed for integration into the system, but instead the gadgets have a system deliberately designed for their promotion (Anon 1979). Another caution is against systems which convert all the primary sources into electricity which is then used to perform the required tasks. This all-electric type of rural energy system violates the principle of a mix of sources to match tasks, and the penalty for this disregard of second-law efficiencies is in the form of extremely high capital costs for the system (Anon 1976).

9. Towards a mathematical approach to rural energy centres

The case study of Pura has been used as an illustrative exercise to reveal the nature and complexity of the problem of rural energy centres and to indicate a heuristic approach. Like all villages, Pura is both unique and typical. Along with 60% of

India's villages, it has a population of under 500. Like a large part of India, Pura is in a dry and backward area, and shows little impact of modernisation. Another typical feature of Pura is its human-to-cattle ratio of 2:3 which is not very different from the all-India average of 2. But, the energy problem of Pura is bound to be fundamentally different from the problems of a village in the cold mountains, windy coasts, forests or deserts.

To handle this variety of villages, and therefore of rural energy problems, it would be advantageous to develop a mathematical approach to rural energy systems. Towards this end, a preliminary attempt at a mathematical formulation of the problem of rural energy centres is indicated below.

As stated earlier, the fundamental problem of designing a rural energy centre for a particular village is to find the optimum way of using its m accessible sources in n possible devices to perform the p tasks corresponding to its energy needs.

The first constraint is that the total energy supplied by the sources should be equal to the requirements of the tasks. Defining A_k as the total energy requirement (e.g., in kcal) of the kth task and A_{ijk} as the quantity of energy obtained when source i is used *via* device j to perform this kth task, the condition is that

$$A_k = \sum_{i=1}^{m} \sum_{j=1}^{n} A_{ijk} = \sum_{i=1}^{m} \sum_{j=1}^{n} r_i \, \eta_{ijk} \, x_{ijk}, \tag{1}$$

$$k = 1, 2, \ldots, p,$$

where r_i is the energy equivalent (e.g., kcal/kg, kcal/m^3, etc.) of the source i, η_{ijk} is the first law efficiency* for the path ijk defining the ratio of the energy output to the energy input, and x_{ijk} the quantity (in kg, m^3, etc.) of resource i used *via* device j for task k.

The second constraint is that there is an upper limit for all local energy sources. Defining R_i as the maximum energy *locally* available per annum from the ith energy source ($i = 1, 2, \ldots m'$, where the m' local energy sources are a sub-set of the set m of all energy sources), the condition is that

$$R_i \geqslant \sum_{j=1}^{n} \sum_{k=1}^{p} r_i \, x_{ijk} \geqslant r_i \sum_{j=1}^{n} \sum_{k=1}^{p} x_{ijk}, \tag{2}$$

$$i = 1, 2, \ldots m'.$$

The third constraint is that some tasks have definite power requirements, i.e., they demand that the requisite energy be supplied within a certain time. If P_k is the maximum power required by the *individual* user of a device performing the kth task and P_{ijk} is the maximum power available for this task from a source i *via* device j, the condition can be written thus:

$$x_{ijk} = 0 \text{ if } P_{ijk} < P_k. \tag{3}$$

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*η_{ijk} is assumed here to be independent of x_{ijk}, i.e. there are no efficiencies of scale. This assumpion is reasonable if (a) devices are used whose number is proportional to the energy input (e.g., one device per household), and (b) the scale of devices used in villages is in a range within which the efficiency is almost constant.

Thus, the power condition can be used *a priori* to eliminate those source-device combinations which cannot yield adequate power for the task. In case there is a possibility of combining sources in devices, the above condition must be written for the combined power of the sources, i.e.,

$$x_{ijk} = 0 \text{ if} \sum_i P_{ijk} < P_k. \tag{4}$$

It is also essential that the sum of the power *outputs* of the *i*th energy source through all the paths *ijk* should not exceed the maximum power $P_i^{\max}$ which this source can develop, i.e., the condition is

$$P_i^{\max} \geqslant \sum_{j=1}^{n} \sum_{k=1}^{p} P_{ijk} \text{ (output)}. \tag{5}$$

But P_{ijk} is the contribution of the power *output* from the *i*th source *via* the *j*th device to the total power required by the *k*th task; hence

$$P_{ijk} \text{ (output)} = (A_{ijk}/A_k)\, P_k = (r_i\, \eta_{ijk}\, x_{ijk}/A_k)\, P_k. \tag{6}$$

The corresponding power *input* from the *i*th source must reckon with the efficiency η_{ijk} of power conversion*, i.e.,

$$P_{ijk} \text{ (input)} = (r_i\, \eta_{ijk}\, x_{ijk}/A_k)\, (P_k)\, (1/\eta_{ijk}). \tag{7}$$

Hence, the total power *input* required of the *i*th source is

$$P_i \text{ (input)} = r_i \sum_{k=1}^{p} (P_k/A_k) \sum_{j=1}^{n} x_{ijk}. \tag{8}$$

If there is a possibility of the loads corresponding to the various tasks occurring at different times, it is also necessary to introduce a diversity factor for each source:

$$d_i = \frac{\text{sum of individual maximum loads at a given time}}{\text{total maximum load}}. \tag{9}$$

Hence, the condition is

$$P_i^{\max} \geqslant (r_i/d_i) \sum_{k=1}^{p} (P_k/A_k) \sum_{j=1}^{n} x_{ijk}. \tag{10}$$

The design of the rural energy centre can be based on several objectives. The obvious one is minimisation of the total annual cost C of the rural energy centre. If C (cap) and C (op) are the annual charges arising from the capital investment and

*If the averages of output and input power are considered, η_{ijk} is both the power efficiency as well as the energy efficiency.

operational requirements respectively, then the objective function which has to be minimised is

$$C = C\,(\text{cap}) + C\,(\text{op}). \tag{11}$$

As a first approximation†, the annual costs arising from the capital investment and operational charges for source i can both be assumed to be proportional to the quantity of source i which is utilised, i.e.,

$$C\,(\text{cap}) = \sum_{i=1}^{m} C_i\,(\text{cap}) = \sum_i \sum_j \sum_k a_{ijk}\, x_{ijk}, \tag{12}$$

and

$$C\,(\text{op}) = \sum_{i=1}^{m} C_i\,(\text{op}) = \sum_i \sum_j \sum_k b_{ijk}\, x_{ijk}, \tag{13}$$

where the constants of proportionality, a_{ijk} and b_{ijk}, represent the annual capital charges and operational costs respectively per unit quantity of source i used *via* device j to accomplish task k.

The constants implicitly involve second-law efficiencies, but this feature can be brought out explicitly since it can be shown that

$$a_{ijk} = \frac{\theta_i\,(\text{cap})\, u_{i^*j^*}\,(\text{cap})}{\eta_{i^*j^*k}\ \epsilon_k\ \eta_{ijk}} \text{ and } b_{ijk} = \frac{\theta_i\,(\text{op})\, u_{i^*j^*}\,(\text{op})}{\eta_{i^*j^*k}\ \epsilon_k\ \eta_{ijk}}, \tag{14}$$

$$a_{ijk} = (a'_{ijk}/\epsilon_k) \text{ and } b_{ijk} = (b'_{ijk}/\epsilon_k), \tag{15}$$

where the θs represent the ratio of the costs of using the sources and devices i and j to the costs of using the ideal source and device i^* and j^*, the $u_{i^*j^*}$s, the costs of using the ideal source and device i^* and j^* per unit quantity of source used, the ηs are the first-law efficiencies and ϵ_k the second-law efficiency for the kth task.

The preference for local, renewable sources can be introduced by using multipliers thus: $\alpha_i \geqslant 1$ for non-local sources and $\beta_i \geqslant 1$ for non-renewable sources. That is,

$$C\,(\text{cap}) = \sum_{i=1}^{m} \alpha_i\, \beta_i \sum_{j=1}^{n} \sum_{k=1}^{p} a_{ijk}\, x_{ijk}. \tag{16}$$

The fundamental problem of rural energy system design can now be stated††:

Minimise C where

$$C = \sum_{i=1}^{m} \alpha_i\, \beta_i \sum_{j=1}^{n} \sum_{k=1}^{p} \frac{a'_{ijk}}{\epsilon_k}\, x_{ijk} + \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} \frac{b'_{ijk}}{\epsilon_k}\, x_{ijk}. \tag{17}$$

†The approximation is completely valid when the annual capital and operational costs arise from devices whose number is proportional to the quantity of energy source used, e.g., when there is one device per family. It is also valid when the scale of devices used in villages is in a range within which there are hardly any economies.

††Other formulations of the problem are also being considered, e.g., maximising task satisfaction subject to limitations on the availability of energy sources.

Subject to the following conditions:

(i) $\sum_{i=1}^{m} r_i \sum_{j=1}^{n} \eta_{ijk}\, x_{ijk} = A_k$ (needs satisfaction), (1)

$$k = 1, 2, \ldots, p,$$

(ii) $r_i \sum_{j=1}^{n} \sum_{k=1}^{p} x_{ijk} \leqslant R_i$ (resource availability), (2)

$$i = 1, 2, \ldots, m' \leqslant m,$$

(iii) $\frac{r_i}{d_i} \sum_{k=1}^{p} \frac{P_k}{A_k} \sum_{j=1}^{n} x_{ijk} \leqslant P_i^{\max}$ (total power availability), (10)

(iv) $x_{ijk} \geqslant 0$ for all i, j and k. (18)

The following set of conditions:

$x_{ijk} = 0$ if $P_{ijk} < P_k$ (power availability for individual devices), (19a)

$\eta_{ijk} = 0$ if periods of source supply and demand do not overlap, (20a)

can be introduced into the problem as an *a priori* check and by setting the values of the corresponding x_{ijk}'s and η_{ijk}'s equal to zero. Or, the objective function can be modified by adding multipliers γ_{ik} and δ_{ik}

$$\gamma_{ik} = 1 \quad \text{if } P_{ijk} \geqslant P_k,$$

$$\geqslant 1 \quad \text{if } P_{ijk} < P_k, \tag{19b}$$

and $\delta_{ik} = 1$ if periods of source supply and task demand overlap,

$\delta_{ik} \geqslant 1$ if supply and demand periods do not overlap. (20b)

The above approximation of the general problem has a linear objective function (costs) and linear constraints. Further, the variables are non-negative. Hence, it is a linear programming problem* which can be solved by simplex or revised simplex procedures. It is in fact a three-dimensional transportation problem.

Despite the reduction in complexity in the ' linear ' version of the general problem, a solution is possible only after a large amount of data is available. The merit of the mathematical formulation of the problem presented here is that it has identified what information is required for the optimal design of rural energy systems or centres.

*If, however, there are marked economies and efficiencies of scale even for the scales of devices reasonable for villages, then the linear approximations are no longer valid, and the problem becomes a non-linear programming exercise.

It has highlighted the importance of quantifying, with respect to magnitude and time, the energy requirements of all the tasks and the availability of energy sources—all these are region-specific and location-specific. It has also emphasised the importance of data on the first-law efficiencies of all feasible devices, the second-law efficiencies of all tasks, the unit costs of source utilisation, and the power requirements of various tasks—these are technology-specific and cost-specific.

10. Acceptability of rural energy centres

However technically perfect the design of a rural energy centre may be, there is no guarantee that the system is consistent with development objectives. To ensure this consistency, additional criteria must be used, e.g., whether the rural energy centre satisfies the energy component of basic needs, particularly the needs of the neediest, and fulfils the desire for local self-reliance. The problem of assessing designs for rural energy systems from the standpoint of the wider social perspective is far more complex, and the methodologies are in the embryonic stage (Reddy 1979). But, these are matters which go beyond the scope of this paper.

Nevertheless, one conclusion is clear: for a ' technological solution ' to be accepted into the matrix of society, it has to satisfy vital non-technical social criteria. Rural energy systems, therefore, must be society-specific and culture-specific. There cannot be standardised designs and packages for universal application. Rural energy centres cannot be mass-produced.

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A methodology for evaluating appropriateness of new energy resources in rural applications

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Abstract. In this paper a method to determine the appropriateness of energy resources in rural applications is discussed. Feasible energy resources are comparatively evaluated using eight attributes representing the criteria of appropriateness. 'Appropriateness' is defined as a linear combination of attribute weights multiplied by attribute attainment levels which have been mapped into utility for decision-makers. The uncertainty in data is handled using Monte-Carlo techniques. Sample results indicate a set of dominant energy resources for a particular task. This method can be applied in real-life decision making concerning energy resources for rural applications.

Keywords. Appropriateness index; alternate energy conversion; attribute levels; utility mapping; Monte-Carlo techniques.

1. Introduction

The four-fold increase in the price of oil announced by the Oil Producing and Exporting Countries (OPEC) in 1973 brought into sharp focus the need to consider alternative sources of energy such as biogas, solar energy, wind power, energy from the ocean waves, etc. Many research and development programmes aimed at utilising these energy resources are being pursued in India and elsewhere. Of these renewable energy resources are more attractive in the long run and therefore deserve consideration even if they are more expensive than fossil fuels. An attempt is made in this paper to present a methodology for evaluating the appropriateness of an energy resource in the rural context.

In the last few years, data regarding the Indian rural energy scene has been published (Anon 1974, Makhijani 1976, Revelle 1976, Reddy & Prasad 1977), which provide a general idea on the utilisation of conventional energy resources—both commercial and non-commercial in the rural context. Attempts have also been made to highlight possible applications of newer energy resources, particularly biogas. The report of the US National Academy of Sciences (Anon 1976) presents a state-of-the-art picture of solar energy, wind power, mini-hydel power, Stirling engines and a few other newer energy conversion systems.

However, no one particular conventional energy resource is suitable to meet the total energy demand for all the tasks in the rural sector. For instance, although firewood is used in domestic cooking, it has not yet been made use of for water pumping using external combustion steam engines. Similarly, electricity is only used for irrigation pumpsets or domestic lighting and not for domestic cooking.

Consequently, it has become necessary to examine the appropriateness of an energy resource with particular reference to a task or a group of tasks according to its priority.

2. Identification of task and energy resources

Energy is required in various agricultural operations such as tilling for seedbed preparation, application of fertilisers and insecticides, irrigation, harvesting, grain drying, transportation of the produce, etc. Irrigation, so crucial in agriculture, is gradually being extended to cover a major part of the cultivated land of the country. Ground water roughly covers one third of the water requirement of irrigated land and if this proportion is maintained, the demand for energy to pump ground water is expected to increase. At present electricity in rural areas is mainly used for irrigation pumpsets. However, the high cost of rural electrification is a severe constraint. There is therefore considerable scope for decentralised water-pumping systems based on the newer energy resources.

Small and marginal farmers with land holdings of about one hectare deserve priority in any rural development programme. These farmers cannot afford diesel and electrical pumps and if the government can provide them with water pumps on easier credit terms or subsidies, it would help evaluate appropriateness of conventional and new energy resources so that the support is channelled in the best possible manner. Taking a unit area of 1 hectare and the typical water requirement for irrigation per season for non-rice food crops as 500, mm and assuming a head for water pumping of about 10 m, the total energy requirements amount to 136 kWh per hectare per season or approximately 1 kWh per hectare per day. We must however bear in mind that about 15–20 kWh of energy may be required at a stretch for each irrigation and that about 6–7 such irrigations may be required during a four-month season.

The following water pumping systems can provide a work output equivalent to 1 kWh per day:

(i) bullock-powered traditional waterlifts,
(ii) diesel-powered pumpsets,
(iii) electrical pumpsets,
(iv) biogas generated in family size units (2–3 m^3/day) for energising liquid piston pumps,
(v) biogas generated in large community size plants and utilised in modified diesel engines,
(vi) solar thermal devices driving water pumps,
(vii) solar-pump without moving parts,
(viii) photovoltaic arrays driving electrical pumpsets,
(ix) wind-powered pumps.

While small water wheels, hydraulic ram, Stirling engines, geothermal power, etc. can also be used for smaller applications, the cost and performance data available are rather inadequate yet for our analysis. Moreover, these devices except for Stirling engines run on crop residues can operate only at a few favourable locations.

3. Attributes for evaluating appropriateness

The appropriateness of an energy resource in the rural context can be determined by its relationship with rural development. Rural development can be stated in simple terms as the problem of providing gainful employment to people in villages in the quickest possible time with a reasonable expenditure of resources (including finances) and in a manner consistent with the lifestyle of the people. Viewed from this angle, the following attributes can be identified in order to assess the appropriateness of energy resources:

(i) capital cost of energy conversion devices,
(ii) recurring costs,
(iii) energy technology availability: time factor,
(iv) priority for the use of the resource under consideration in a given application,
(v) organisational and maintenance aspects,
(vi) social acceptance,
(vii) generation of local employment,
(viii) use of locally available fuels or materials.

The capital cost would be determined from the installed capacity, say, per kilowatt. The cost of the prime-mover, driven loads such as pump and generator, the energy or output storage system (such as batteries and water tank for irrigation) etc. may also have to be included here depending upon the particular energy resource under consideration. Running costs would be determined from depreciation, fuel charges and the cost of operation and maintenance. The running cost can be expressed for one full year or in terms of a fraction of a year, e.g. a crop season. The third attribute concerns the time factor involved in making available to the users a particular energy technology, e.g. energy conversion device. This factor is important because several newer energy resources are at different stages of research and development. The fourth attribute refers to a possible social priority in the use of limited resources in a variety of applications. For instance, if the biogas potential is found to be limited, the society might allot a higher priority for its use in cooking than in irrigation water pumping. In the supply of fuel and the distributing energy, some organisational problems may develop. In addition to this, the maintenance and operation of the devices would also require attention. These aspects are covered in the fifth attribute. The sixth attribute concerns the social acceptance of new energy conversion systems. Such of those energy conversion systems which disturb the lifestyle, which are potentially hazardous and which interfere with religious beliefs are likely to be less acceptable to society. Employment generation in villages for the construction, maintenance and operation of energy conversion systems is the next attribute, which is directly related to rural development. The last attribute relates to the use of locally available fuel, which is highly desirable for a variety of reasons, apart from the low cost and easy and ready accessibility.

The attributes—capital and running costs—can be expressed in rupees. Technology availability can be expressed in years or months and employment generation in terms of mandays. The remaining attributes are qualitative in nature and can be specified in terms of grades like very high, high, medium, low and very low. In

numerical terms, these grades can be expressed on a five-point scale ranging, say, from 1 to 5.

4. Appropriateness index

The appropriateness of energy resources can be expressed mathematically as a combination of ratings obtained in respect of each attribute. Thus, the appropriateness index for the jth alternative energy conversion system or resource can be expressed as

$$A_j = \sum_{i=1}^{8} f_{ij}(x_i), \tag{1}$$

where the x_i are the attributes and $f_{ij}(x_i)$ indicate the scores obtained in respect of each attribute. The expression $f_{ij}(x_i)$ includes the following two basic considerations:

(i) all attributes need not be equal and some may be more important than others;
(ii) the value of attaining a certain score in terms of the attribute scales.

These aspects are discussed in the subsequent sections.

5. Relative importance of attributes

The weighting of multiple criteria or attributes is a standard technique in the application of scoring models such as the one given in equation (1). Examples are available in the literature on the application of ranking, rating, paired comparison, the successive comparison method of Churchman, and a few other methods. The authors conducted an opinion poll among eleven participants who were requested to rank the given eight attributes. Of the eleven participants, one was directly involved in rural development, one in energy planning, one from industry, one from R & D

Table 1. Ranks assigned to eight attributes

	Attributes						
	1 & 2*	3	4	5	6	7	8
1	1	3	7	2	4	6	5
2	6	7	5	4	3	1	2
3	3	2	7	1	6	4	5
4	2	4	6	5	1	7	3
5	2	1	5	4	7	3	6
6	2	3	7	4	1	5	6
7	5	1	2	3	6	4	7
8	3	7	1	4	5	6	2
9	2	1	7	5	3	4	6
10	4	7	6	3	5	2	1
11	1	2	6	4	7	3	5

*In the exercise that was carried out, the two costs were combined together.

management, three in R & D on renewable energy resources and four from the academic profession. Ranks were provided from one to eight and this information is presented in table 1. An application of Kendall's (1962) test indicated a low value of concordance; that is, agreement among the participants about rankings was not high enough. At the same time it is not entirely random as found through an application of the Chi-square test.

To rank the attributes, the participants (i.e., decision-makers) were asked to assign values between 1 and 100 in respect of each attribute. These values were normalised and the frequency histograms shown in figure 1 were obtained. The abscissae in figure 1 represents the weight scale ranging from 0 to 1, divided into twenty equal intervals. The frequency of occurrence, that is, the percentage of the number of people who assigned scores falling within a particular weight interval is shown along the ordinate. In figure 1, the expected values for the weights are also shown. The third attribute, technology availability, obtains the highest value (0·17), and priority for use in irrigation obtains the lowest value (0·09). Other attribute weights range from 0·11 to 0·16. These weights appear reasonable and imply that early availability of energy technology and lower costs are surely the most important criteria.

Let the weights given in figure 1 be denoted by w_i where i represents the attribute.

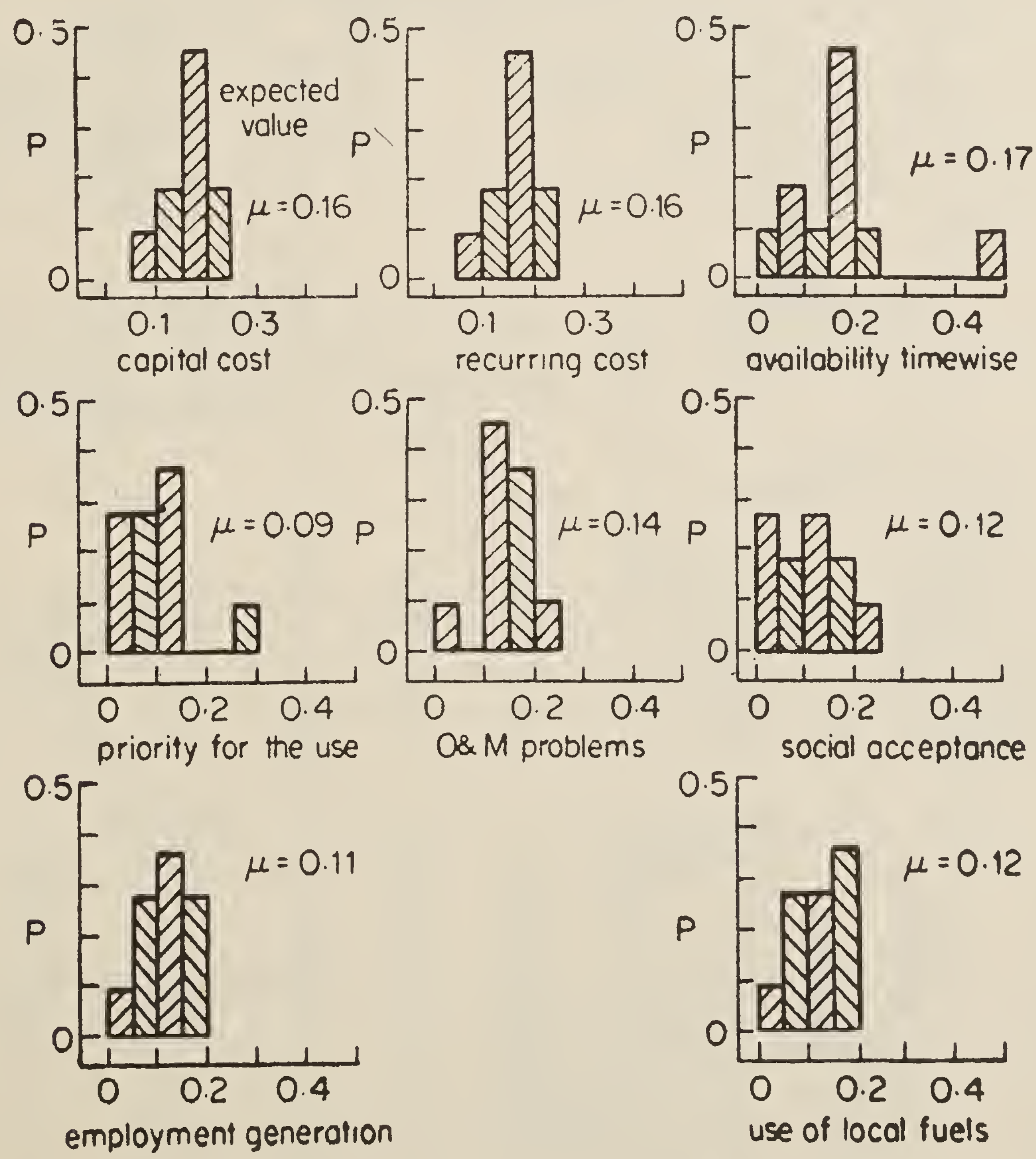

Figure 1. Frequency histograms for attribute weights.

6. Attribute levels

In our present decision-making problem, the attributes have two characteristics. The first is that these attributes appear with scales of attainment and not as goals which are either achieved or not achieved. The second characteristic is that each attribute for a given energy resource appears with a range of values rather than with one fixed value. To be specific, consider wind-powered pumps. To provide 1 kWh per hectare per day on an average, during the *rabi* season (the main irrigation season from November to February), the swept rotor diameter may have to be of the order of 10 m providing an equivalent swept area of $78 \cdot 5\,m^2$. Prototype windmills having swept areas ranging from 8 m^2 to $78 \cdot 5\,m^2$ have been reported (Govindaraju & Narasimha 1979; Vilstern 1978; Sherman 1976; Smith 1976; Tyabji 1977; Tewari *et al* 1979). From the information available on these designs, one might assume that the capital cost for our wind-powered pumps will range from Rs 5,500 to Rs 13,500. This range would accommodate such variables as windspeeds, choice of construction material, design and fabrication techniques, labour charges, etc. Further, it would be reasonable to assume that the probability of the cost being either Rs 5,500 or

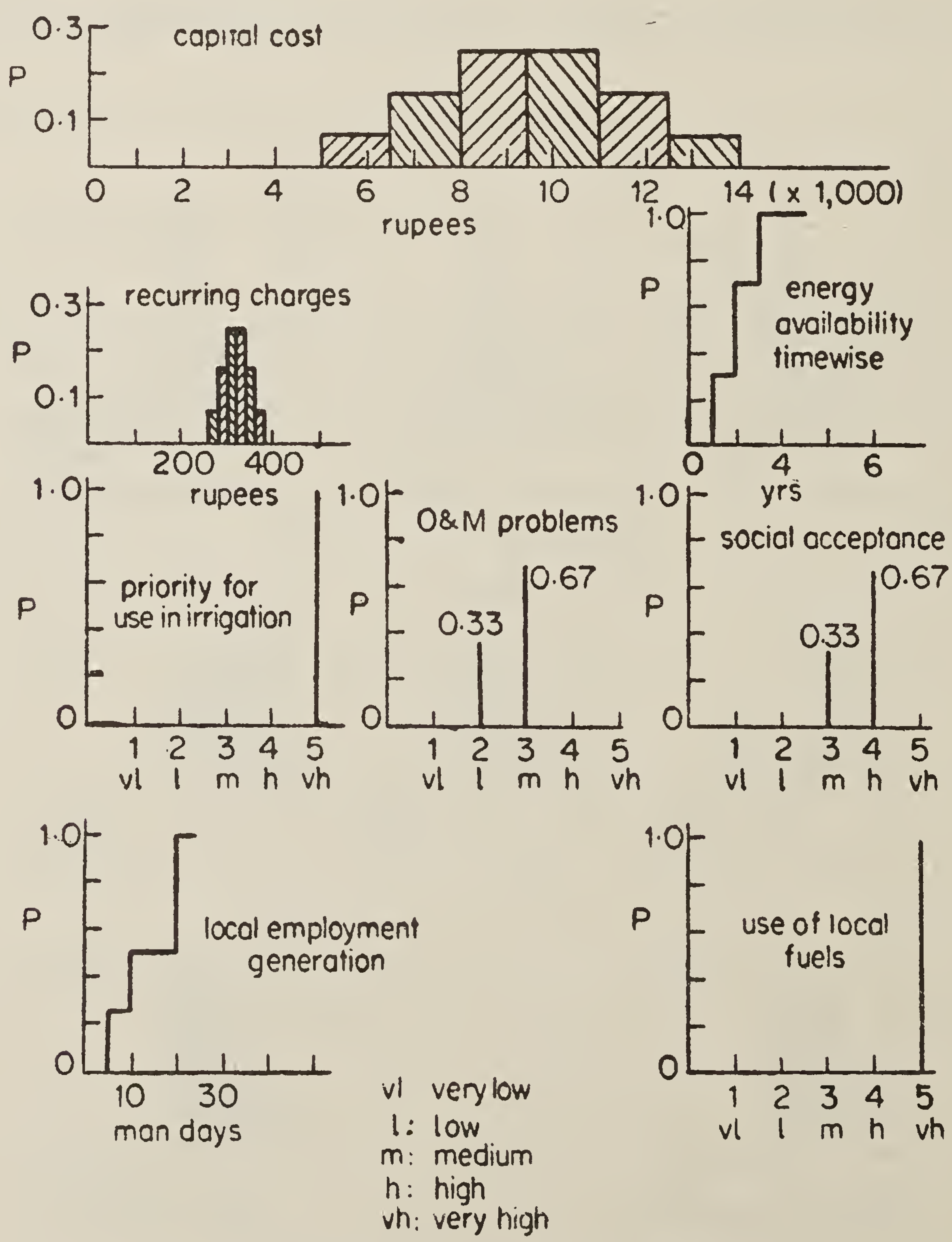

Figure 2. Attribute attainment levels for wind-powered pumps.

Table 2. Attribute attainment levels.

Alternatives (energy conversion systems)	Capital cost (Rs) (normal distribution)	Recurring charges (Rs) (normal distribution)	Technology availability —timewise (years) (linear distribution)	Priority for use	O & M problems	Social acceptance	Local employment generation (man-days)	Use of local fuels
	Attributes (probabilities shown in brackets)							
1. Bullock-powered waterlifts	1,250– 2,750	140–210 + 450–900	½	H (67%) VH (33%)	VL (67%) L (33%)	VH	3	VH
2. Electrical pumpset	8,000–19,000	14– 70 + 125–325	0 (32%) 12 (100%)	H (67%) VH (33%)	M (50%) H (50%)	VH	12	VL
3. Diesel-powered pumpsets	3,550– 5,500	110–190 + 210–330	½	M (50%) H (50%)	H (33%) VH (67%)	VH	2	VL
4. Family-size biogas plant energising liquid piston pumps	2,800– 3,800	250–290	1½ (0%) 3½ (100%)	L (33%) M (67%)	L (33%) M (67%)	L (50%) M (50%)	6	VH
5. Community-size biogas plant energising modified diesel pumpsets	600– 1,200 + 3,500– 5,500	160–220	1½ (0%) 3 (100%)	L (33%) M (67%)	H (33%) VH (67%)	M (50%) H (50%)	6	VH
6. Solar-thermal devices	16,000–28,000	490–690	2½ (0%) 5 (100%)	VH	H (33%) VH (67%)	H (33%) VH (67%)	6	VH
7. Solar-pump without moving parts	27,000–51,000	550–960	3½ (0%) 6 (100%)	VH	M (33%) H (67%)	VH	6	VH
8. Photovoltaic systems	9,000–13,000 (assuming US D.O.E. goals of $1 per peak watt are achieved by mid 80s.	100–140	4 (0%) 9 (100%)	VH	VL (67%) L (33%)	VH	0	VH
9. Wind-powered pumps	5,500–13,500	2603–80	½ (0%) 2 (100%)	VH	L M	M H	10–20	VH

O & M = operation and maintenance
VH, very high; H, high; M, medium; L, low; VL, very low

Rs 13,500, the two extreme values, would be very small compared to the cost being around Rs 9,000 (the mean value). In other words, for the capital cost, one may assume the probability distribution curve to be normal, as shown in figure 2(a). Similarly, for the same energy converter (i.e., wind-powered pumps), one may determine the probability distribution functions regarding the other attributes also. These are shown in figure 2. Similar analyses can be made for the other energy resources also. In this paper, the details regarding these resources are not given, but the methodology is similar to the one just discussed. The details can be found in Tewari (1978). However table 2 briefly gives these details.

7. Utility mapping

The appropriateness of an energy resource was earlier defined as a combination of scores in respect of the eight attributes. However, the measures of these attributes are not all the same. While capital and operating costs are measured in rupees, the availability of technology is measured in years and social acceptance purely in qualitative terms. Consequently, the scores cannot be combined simply as in equation (1). But if the scores are expressed in terms of some common measure, then one can apply equation (1). One such common measure is the degree of satisfaction to a decision-maker or a group of decision-makers. Following the definition of utility provided by Starr & Zeleny (1977), if the outward aspects of the preferences of decision-makers are quantified then this artifact called 'utility' can be handled mathematically.

Take for example the capital cost. It is obvious that any decision maker—farmer or a policy planner—would surely prefer a lower capital cost. Moreover, a capital cost higher than a reasonable value would be much less preferred. The highest capital

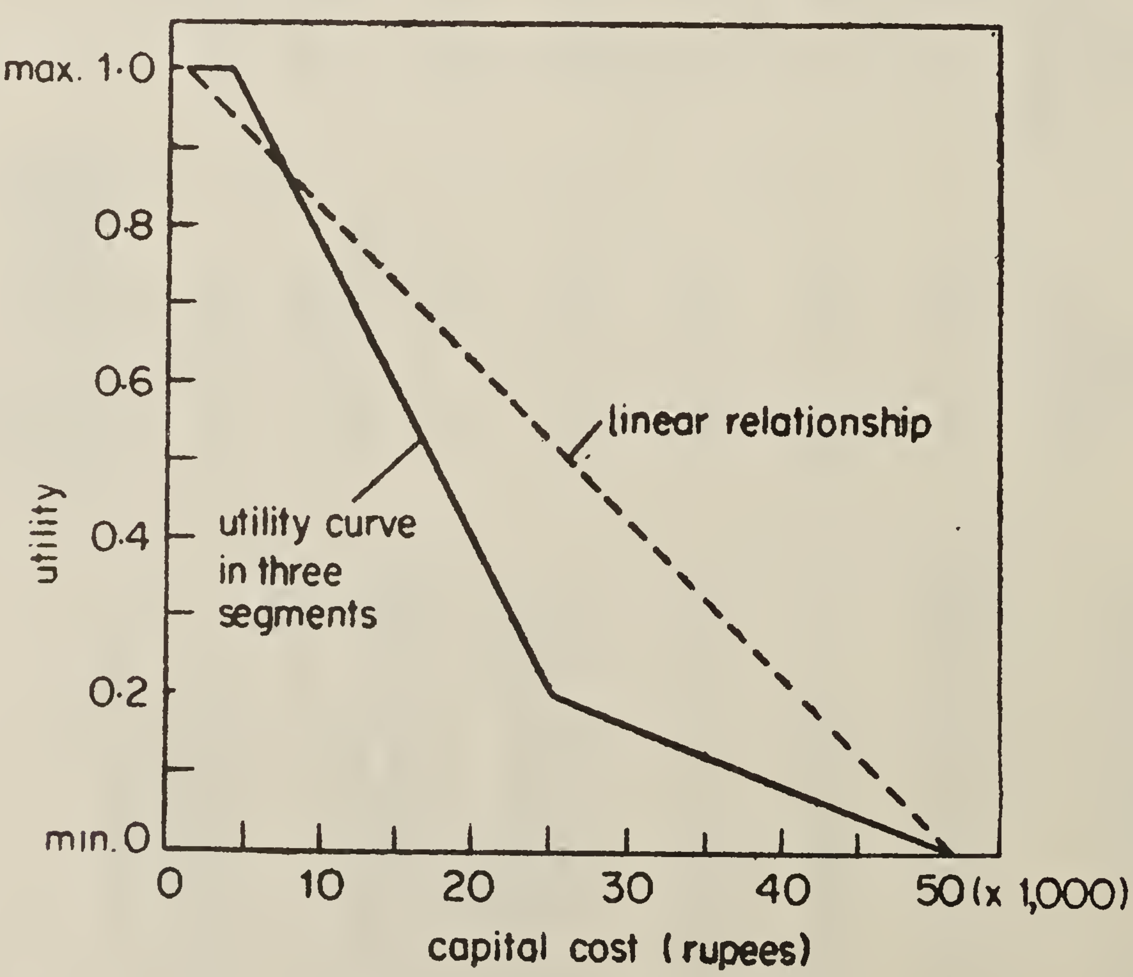

Figure 3. Utility-attribute relationship.

cost encountered among the nine energy resources identified in this study was found to be Rs 51,000 (corresponding to solar pumps without moving parts) and the lowest value was Rs 1,000 (corresponding to bullock-powered waterlifts) (Tewari 1978). Let us define the maximum possible utility as 1 and the lowest possible value as 0. Then we can state that a capital cost of Rs 1,000 amounts to the highest utility (1) and a capital cost of Rs 51,000 obtains the lowest utility (zero). Now, the simplest relationship between utility and attribute-attainment levels would be a straight line joining the extreme ends of the two scales, as shown in figure 3. But, a decision-maker might accord a fairly high utility, higher than that given by the straight line, for capital cost, as long as it remains within what he considers a reasonable value say, Rs 4,000. Thereafter, utility may drop significantly. Beyond a cost of Rs 25,000, which itself is highly undesirable, the utility may slowly decrease to zero. This logic is graphically displayed by means of the three-segmented curve shown in figure 3.

Following the above logic which represents one approach, variations can be expected depending upon the preferences and views of decision-makers. An exercise of this procedure in actual practice could include interviews of decision-makers and

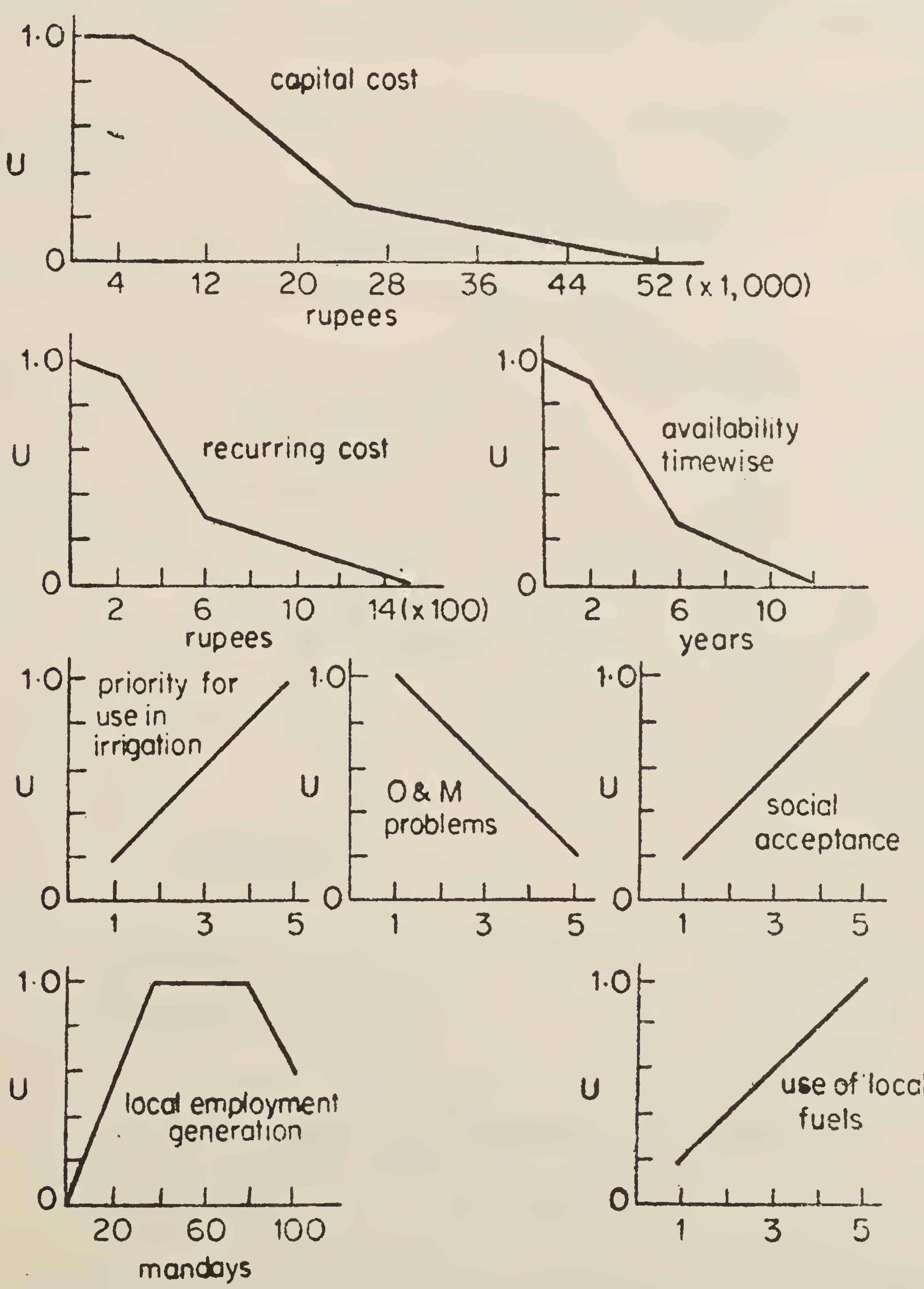

Figure 4. Utility-attribute curves

conducting group discussions. Several techniques have been discussed in the literature such as Keeney's (1972) N & M lottery method, Miller's (1970) method and the direct technique of Edward (1977). The technique discussed here is based on Edward's method, which was applied by him in several examples of social decision-making.

Similar utility-attribute curves can be drawn for the other attributes. These are given in figure 4. In the case of qualitative attributes, the relationship is shown as a straight line. This is expected to be sufficient here since precise quantification of the attribute itself is not possible and therefore any further refinement in utility curves would be a mere exercise.

At this stage, we have two important sets of information. One is regarding the probability distribution versus attribute level for a given energy resource and for each attribute. For a wind-powered pumpset, this information is as shown in figure 2. The second deals with the attribute attainment level versus utility, as just discussed in the above sections. This information is shown in figure 4, and applies to all energy resources under consideration. These two sets of information can be combined into one. This resultant set refers to the mapping of utility versus probability curves for each attribute-energy pair. This transformation mapping is simple, since the attribute level is a common variable in both figures 2 and 4. Figure 5 illustrates

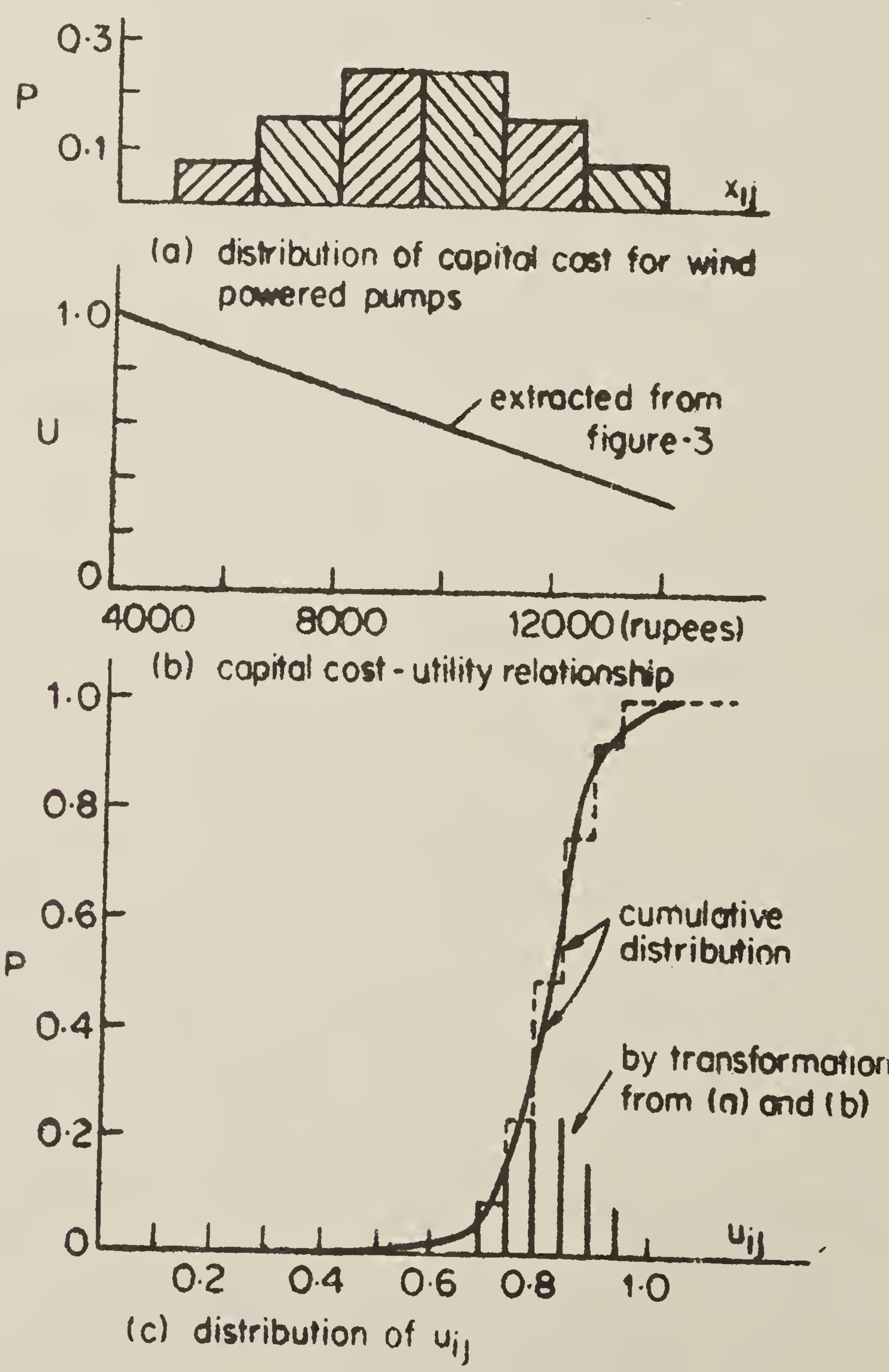

Figure 5. Mapping of attribute levels into utility.

this mapping for the first attribute, *viz.* capital cost and for the energy resource, wind-powered pumpset. The resultant mapping is shown in figure 5(c). If u_{ij} represents the utility of the attribute i for the jth alternative energy resource, then figure 5(c) shows a plot of u_{ij} versus probability distribution.

8. Computation of appropriateness—Monte-Carlo technique

In equation (1), the overall appropriateness or worth of an energy resource is defined as a linear combination of appropriateness in terms of each attribute. The latter denoted by f_{ij} (x_i) consists of two parts, one regarding the importance weights of the attribute themselves that is w_i, and the other connected with attribute attainment levels. To facilitate the combination of quantities with different scales of measurement, we had introduced the mapping of attribute attainment levels into a non-dimensional parameter 'utility'. We recall that u_{ij} represents the utility of the attribute i for the jth energy resource. Therefore we may write

$$f_{ij}(x_i) = w_i u_{ij}. \tag{2}$$

Substituting the above in equation (1), we get for the appropriateness A_j of the jth energy resource

$$A_j = \Sigma_i \; w_i u_{ij}. \tag{3}$$

One difficulty is encountered in computing A_j according to (3). w_i and u_{ij} are not definite quantities, but they appear with their probability distributions. Defining A_j as a quantity jointly distributed over w_i and u_{ij}, which indeed is the case according to (2), the computation can be carried out using the Monte-Carlo technique. According to this technique, random numbers are generated in pairs and their values determine particular values of w_i and u_{ij} to be multiplied. In figure 6, the cumulative distribution of a pair of w_i and u_{ij} corresponding to capital cost for wind-powered pumps (i=1, j=9) is shown. The probability scales are partitioned into intervals to match the steps in the probability curve. Supposing, the random numbers drawn are 0·23 and 0·45; then the values of w_i and u_{ij} read from figures 6(a) and 6(b) are 0·15 and 0·78 respectively. These two are multiplied and stored. The process is repeated eight times corresponding to eight attributes, that is $i=1\ldots8$, but with the same value of j corresponding to wind-powered water pumps. The value of A_j is obtained by adding the results of eight w_i and u_{ij} multiplications. This value of A_j is stored. Next, an additional sixteen random numbers corresponding to eight u_{ij} and eight w_i are generated and the resulting A_j is stored. Supposing this process is repeated 100 times, then 100 values of A_j are obtained, each with equal probability. This information can be readily converted into a frequency histogram and subsequently into cumulative distribution of the type shown in figure 6(c).

The justification for the above procedure in which estimation of A_j is made by using draws of random numbers is based on the law of large numbers. Following Mihram (1972) if x_1, $x_2 \ldots x_n$ are independent random variables from a probability distribution function $f(x)$ having mean μ and variance σ then, for sufficiently large

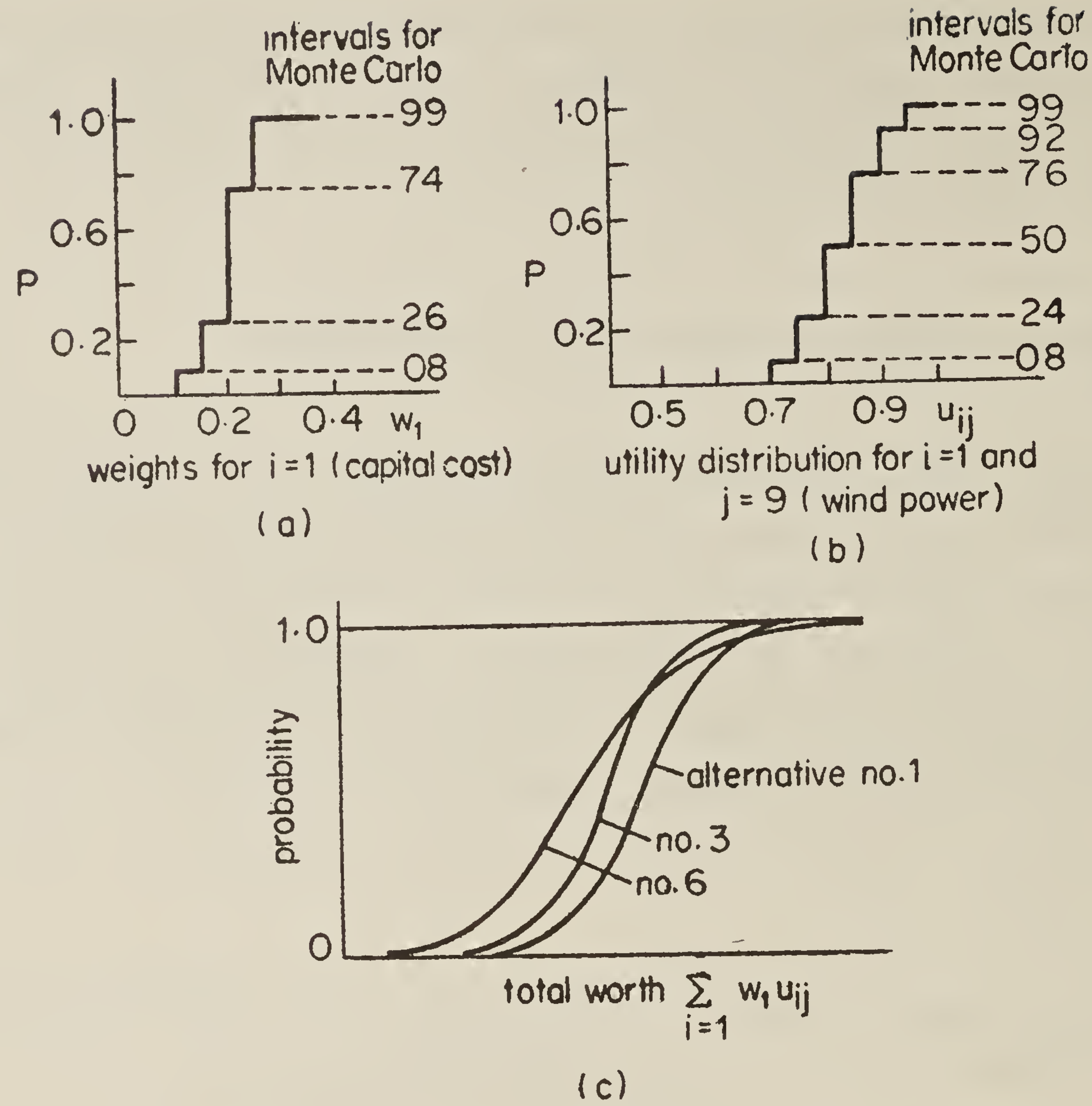

Figure 6. Labelling of random numbers for the application of Monte-Carlo technique

N, their arithmetic mean

$$X_N = N^{-1} \sum_{i=1}^{N} X_i, \tag{4}$$

will in all probability approach μ as the limiting value. In this manner, the mean value of an arbitrary distribution A_j can be estimated by sampling for each w_i and u_{ij} and multiplying the two values each time. By repeating this experiment a large number of times the value so calculated can be deemed to approach the arithmetic mean of the combined distribution $(w_i u_{ij})$.

Pseudo random numbers, sufficient for all practical purposes, can be generated using the mixed congruential method, according to which the kth random number is calculated from

$$U_k = (aU_{k-1} + c) \pmod m, \tag{5}$$

where U_{k-1} is the $(k-1)$th random number (generated earlier), c is an additive constant, and mod m means that the value $(aU_{k-1} + c)$ is divided by m, the remainder being the value of U_k.

In the functional subroutine RANDU the values of the constants are:

$$a = 65.539, m = 2^{31}, c = 2^{32} + 1.$$

With this arrangement, the cycle length, that is, the period after which the chain of random numbers is repeated is quite large. The repetition would occur after

generating 2^{30} random numbers. In our case, if we carry out 500 sampling experiments for each A_j, then the total number required to be generated is just 8,000. So, for all practical purposes the subroutine provides acceptable random numbers for our computation.

9. Illustrative results

The methodology was applied in the case of the task identified in § 2 and the data discussed in § 6. As mentioned earlier, due to limitation of space, it has not been possible to provide details of the analysis of the attribute attainment levels in this paper. The emphasis in this paper is on the methodology and for clarity, some results are provided in figure 7. Without going into the accuracy of the conclusions likely to be inferred from figure 7, the important fact to observe is that in spite of considerable uncertainty in the available data, it is possible to find a clearer pattern of the dominant alternatives.

It is believed that if the exercise is carried out with a group of decision-makers using the latest data and fairly reliable figures, the methodology is likely to be of considerable help in the decision-making process.

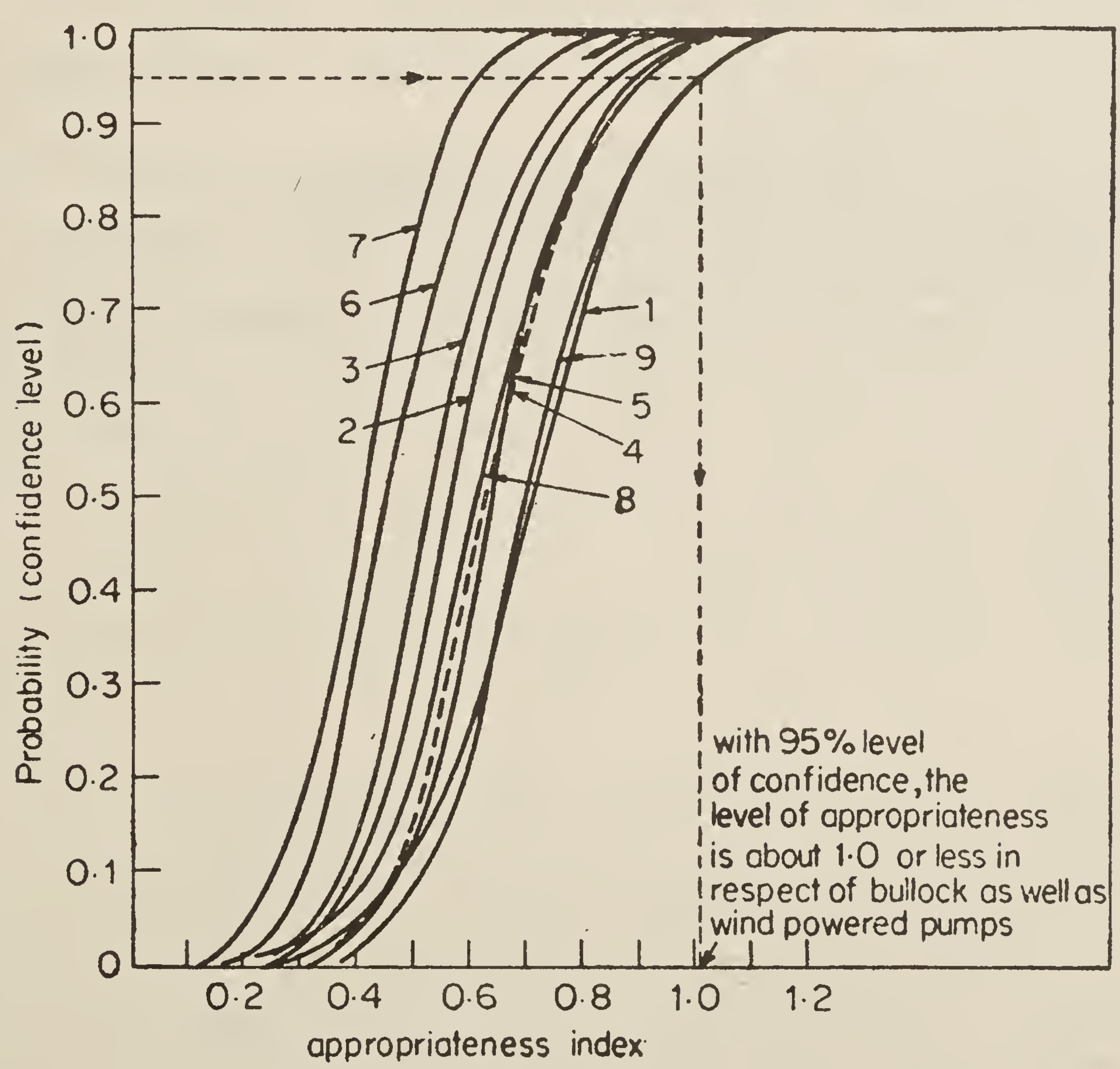

Figure 7. Relative appropriateness of various energy conversion systems. 1. Bullock-powered traditional waterlifts. 2. Diesel-powered pumpsets. 3. Electrical pumpsets. 4. Biogas generated in family size units (2–3 m^3/day) for energising liquid piston pumps. 5. Biogas generated in large community size plants and utilised in modified diesel engines. 6. Solar thermal devices driving water pumps. 7. Solar pump without moving parts. 8. Photovoltaic arrays driving electrical pumpsets. 9. Wind-powered pumps.

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Development of vertical axis wind turbines

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Abstract. This paper summarises the work done at the National Aeronautical Laboratory (NAL) between 1975 and 1977 on the development of vertical axis wind turbines based on the Darrieus rotor. On the analytical side, a performance analysis was developed which permits the estimation of the characteristics of such machines. A 5 m high wind turbine using curved wooden blades was designed, fabricated and tested. Both the theory and initial tests confirmed the low starting torque of the turbine. Wind tunnel tests were performed on model Savonius rotors to determine optimum starter bucket configurations. Finally a straight-bladed turbine was designed and constructed. It is concluded from our experience that Darrieus turbines are likely to be useful in large systems used to generate electrical power for the grid; for direct water pumping purposes, however, these turbines are unlikely to be suitable.

Keywords. Wind turbine; Darrieus rotor; vertical axis windmill.

1. Introduction

Vertical axis windmills have a feature that is particularly attractive—they accept wind from any horizontal direction and do not need the complicated head mechanisms of conventional horizontal axis windmills. The resulting mechanical simplification is sufficient to warrant interest in any new vertical axis concept that arises. During the early seventies, South & Rangi (1971, 1972) conducted wind tunnel tests on a novel vertical axis configuration at the National Research Council, Canada, which showed that the device worked efficiently at high tip speed ratios but had poor starting torque. In effect, the new device behaved much like a low solidity horizontal axis machine but was conceptually a great deal simpler. It appears that the configuration was originally discovered and patented by Darrieus (1931). We refer to this configuration as the Darrieus rotor and when used as a turbine as the vertical axis wind turbine (VAWT).

The Darrieus rotor (figure 1a) consists of a number of curved blades rotating about the vertical axis through their ends. Sections of any blade, in planes normal to the slope of the major (lengthwise) axis, are of aerofoil shape with the chords aligned in the azimuthal direction. One can understand how the device works by studying figures 1b and 1c. These figures show elemental sections of a blade at various azimuthal positions ϕ for a given wind speed V_∞ and at a particular blade angular speed Ω. When the local azimuthal speed $r\Omega$ is large compared with the local wind speed V (figure 1b) the blade element is unstalled for all ϕ as the effective angle of attack α is small (note that dD has been exaggerated in the figure for clarity). In this condition the elemental lift dL contributes positively to the torque while the

elemental drag dD detracts from it. On the other hand, when $r\Omega < V$ (figure 1c), the effective angle of attack can vary from 0° to ±180° i.e. the blade may be stalled or be in reversed flow over part of its trajectory. In this situation the elemental lift can act to reduce the torque and the elemental drag to add to it over a range of azimuthal angles. Since in the stalled case the net forces are often in opposition and since the

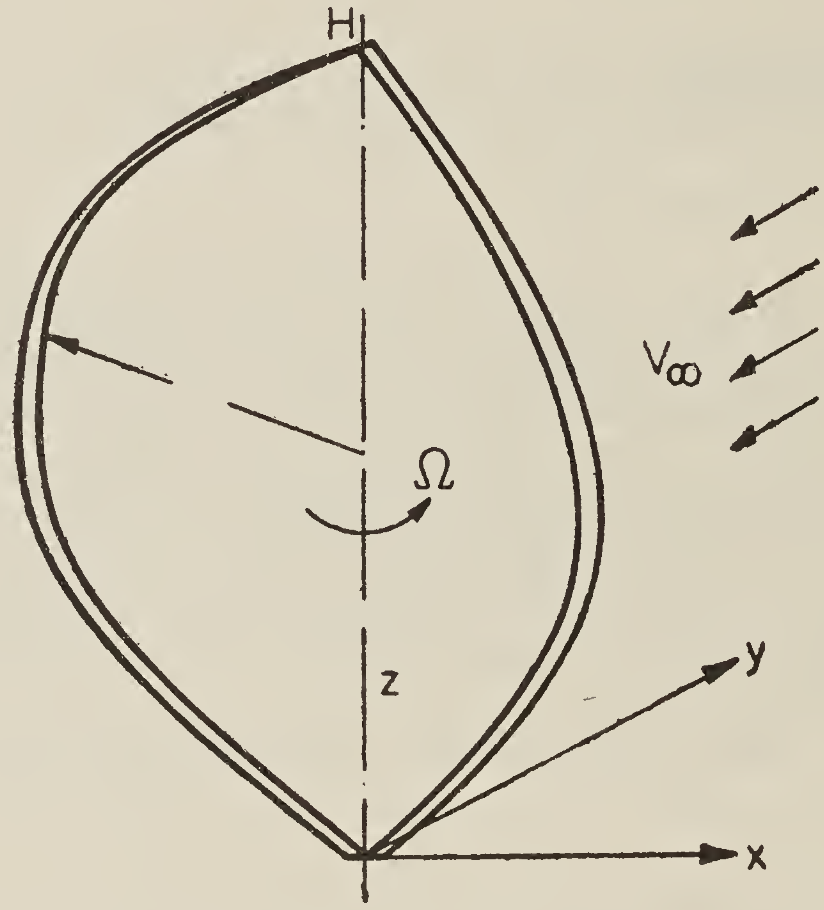

Figure 1a. The rotor geometry. The blades rotate about the vertical axis.

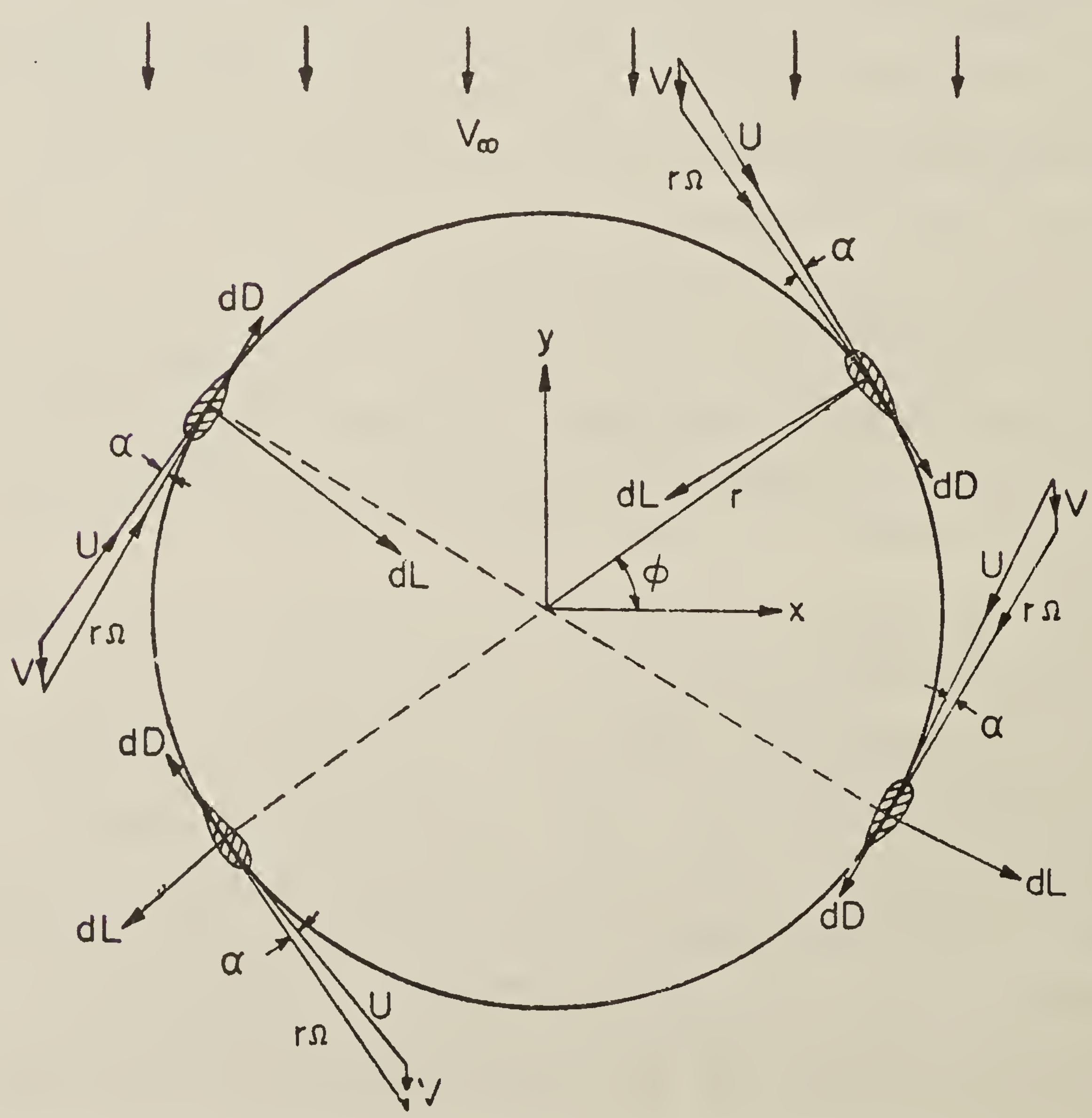

Figure 1b. Angle of attack variations about the azimuth for a blade element whose tip speed $r\Omega$ is large compared to the local wind speed V.

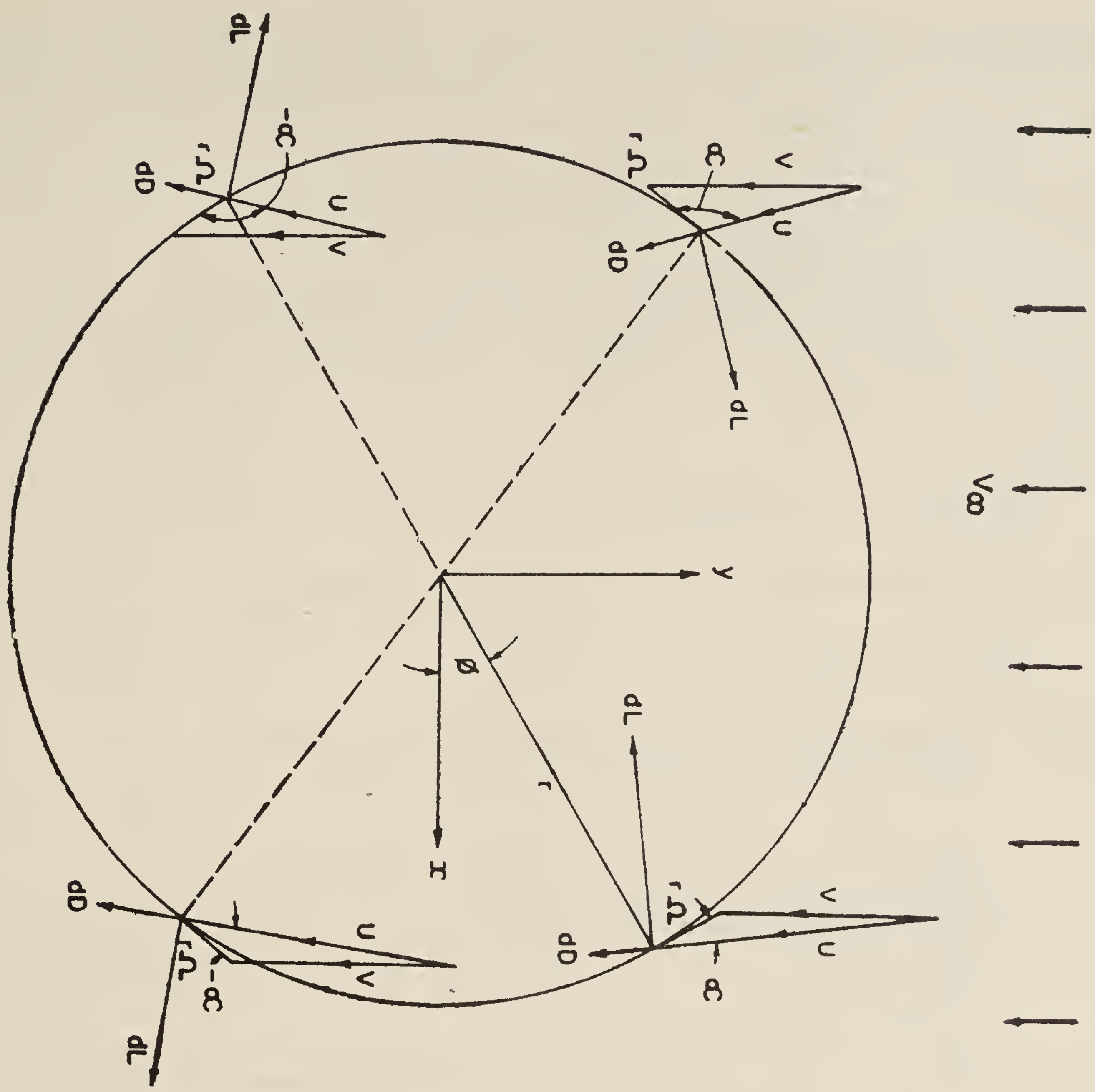

Figure 1c. Angle of attack variations for a blade element whose tip speed is small compared to the local wind speed.

lift-to-drag ratio is normally large in the unstalled case it follows that these machines will operate at high tip speed ratios when at peak power.

Our objective at NAL was to learn and understand the characteristics of Darrieus rotors and to see how feasible they would be in the Indian context. Specific goals were:

(i) to obtain a performance analysis for Darrieus rotors,
(ii) to build a curved bladed machine,
(iii) to study the starting problem, and
(iv) to study the possibility of using straight blades.

The results of our work on these specific tasks are presented in the following sections of this paper.

2. Performance analysis for Darrieus rotors

The Darrieus rotor can be analysed in an elementary way by assuming that each section of a blade behaves as an aerofoil in a two-dimensional flow field. Three-dimensional effects are approximately accounted for by computing the 'induced velocity' from momentum theory. This simple approximate method gives useful estimates that compare reasonably with available experimental data. The method was first used by Templin (1974); an analysis incorporating non-uniform induced velocity is given in Shankar (1975, 1976a) and in Wilson *et al* (1976).

We first consider the induced flow. When a wind turbine operates in an air stream, the wind speed V at the blades will not be equal to the true upstream wind speed V_∞. In taking energy from the wind, the turbine exerts a decelerating thrust on the air stream. One can estimate the deceleration of the stream to a first approximation by replacing the turbine by an actuator disc (figure 2a) in the plane $y=0$. It is assumed in this approximation that the induced velocity in front and back of the rotor are equal, that it is uniform, that the flow is quasi one-dimensional with well-formed slip streams and that all losses are negligible. Under these assumptions the application of the continuity, momentum and energy equations to a large control volume leads to the result

$$V/V_\infty = (1 + \tfrac{1}{4}C'_T)^{-1}, \tag{1}$$

where C'_T is the thrust coefficient based on the local velocity V:

$$C'_T = T/\tfrac{1}{2}\rho A V^2, \tag{2}$$

and A the frontal area of the wind turbine and ρ the air density.

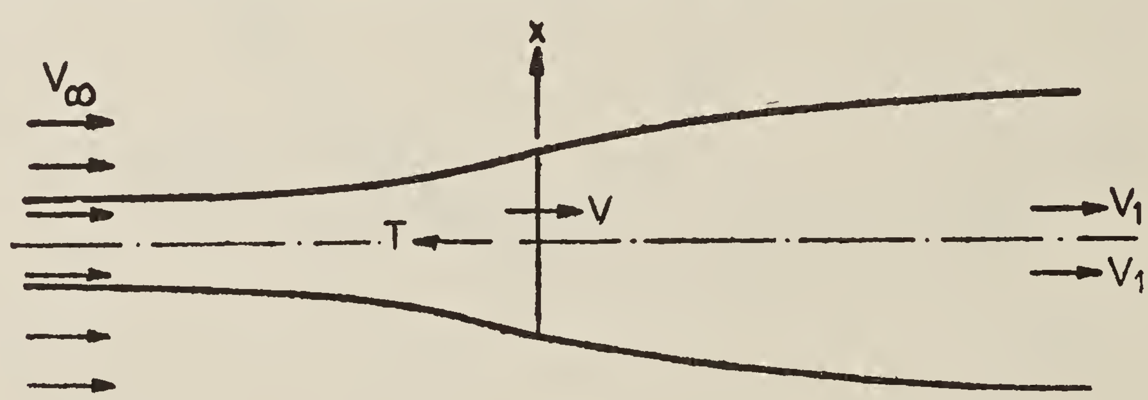

Figure 2a. Actuator disc model of the wind turbine rotor. Here T is the thrust on the wind stream.

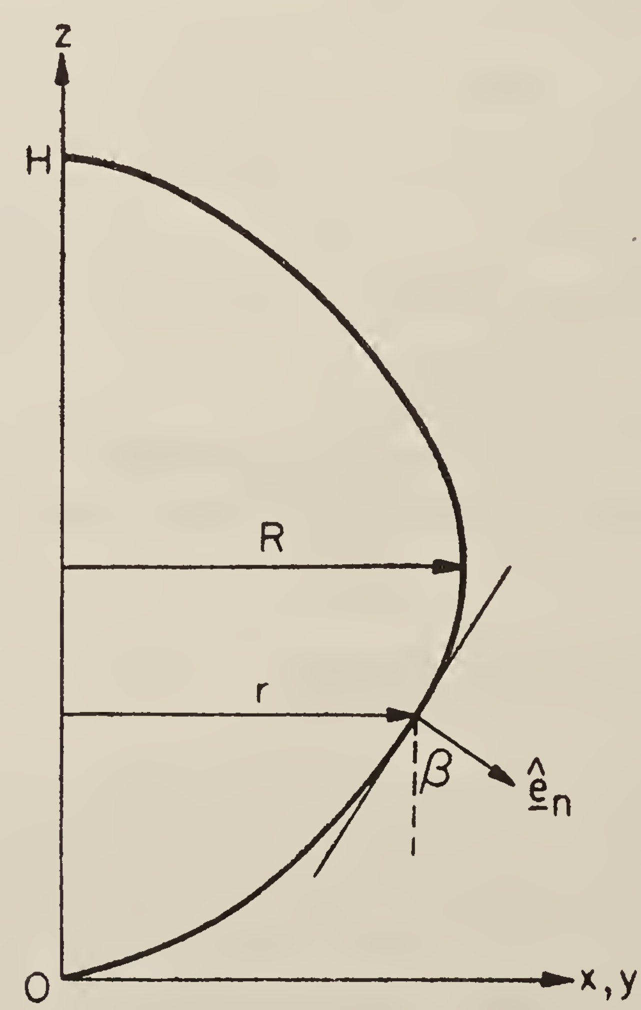

Figure 2b. View of the blade in a direction normal to the plane containing it. $\hat{n}$ is the unit vector normal to the blade chord and to the span-wise tangent to the bladee

At a blade section distance r from the axis (figure 2b) the effective wind speed U contributing to lift and drag is given by

$$U^2 = (r\Omega + V\cos\phi)^2 + (V\sin\beta\sin\phi)^2, \tag{3}$$

while the effective angle of attack α at the section is determined by

$$\tan\alpha = V\sin\beta\sin\phi/(r\Omega + V\cos\phi). \tag{4}$$

If the blade is of chord c with sectional lift and drag coefficients c_l and c_d, the mean power output P and mean thrust T for an N-bladed turbine are given by

$$P = \frac{N}{2\pi}\int_0^H\int_0^{2\pi} \tfrac{1}{2}\,\rho\, U^2 c c_t \frac{dz d\phi}{\sin\beta}, \tag{5a}$$

$$T = \frac{N}{2\pi}\int_0^H\int_0^{2\pi} r\Omega\tfrac{1}{2}\,\rho\frac{U^2 c}{\sin\beta}\,(\sin\beta\sin\phi\, c_n - \cos\phi\, c_t)\, dz d\phi, \tag{5b}$$

where c_t and c_n are the chord-wise and normal force coefficients given by

$$c_t = c_l\sin\alpha - c_d\cos\alpha, \tag{6a}$$

$$c_n = c_l\cos\alpha + c_d\sin\alpha. \tag{6b}$$

If we define the solidity σ, the tip speed ratio μ', power coefficient C'_P and thrust coefficient C'_T based on the local wind speed V as follows:

$$\sigma = \frac{Nc}{\pi R},\ \mu' = \frac{R\Omega}{V},\ C'_P = \frac{P}{k\cdot\frac{1}{2}\rho A V^3},\ C'_T = \frac{T}{\frac{1}{2}\rho A V^2}, \tag{7}$$

where $k = 16/27$ and R is a typical radius, and also normalise the rotor frontal area and other lengths by R

$$A = k_1 R^2,\ \bar{r} = r/R,\ \bar{z} = z/R, \tag{8}$$

equations (5a), (5b), (3) and (4) may be rewritten

$$C'_P = \frac{1}{2\pi k k_1}\int_0^{H/R}\int_0^{2\pi} \sigma\,\mu'\,\bar{r}\left(\frac{U}{V}\right)^2 c_t\,\frac{d\bar{z}d\phi}{\sin\beta}, \tag{9a}$$

$$C'_T = \frac{1}{2\pi k_1}\int_0^{H/R}\int_0^{2\pi}\sigma\left(\frac{U}{V}\right)^2\{\sin\phi\sin\beta\cdot c_n - \cos\phi\, c_t\}\,\frac{d\bar{z}d\phi}{\sin\beta}, \tag{9b}$$

$$(U/V)^2 = (\bar{r}\,\mu' + \cos\phi)^2 + (\sin\phi\sin\beta)^2, \tag{9c}$$

$$\tan\alpha = \sin\beta\sin\phi/(\bar{r}\mu' + \cos\phi). \tag{9d}$$

In practice we require the tip speed ratio μ, power coefficient C_P and thrust coefficient C_T based on the true wind speed V_∞. By using (1) for the induced velocity we obtain

$$\mu = \mu' V/V_\infty = \mu'(1 + \tfrac{1}{4}C'_T)^{-1}, \tag{10a}$$

$$C_T = C'_T (V/V_\infty)^2 = C'_T(1 + \tfrac{1}{4} C'_T)^{-2}, \tag{10b}$$

$$C_P = C'_P (V/V_\infty)^3 = C'_P (1 + \tfrac{1}{4} C'_T)^{-3}. \tag{10c}$$

The calculational procedure is then as follows. With the blade and rotor geometry given C'_P and C'_T are computed as functions of μ' by evaluating the integrals (9a) and (9b). Once these have been computed the true tip speed ratio μ, power coefficient C_P and thrust coefficient C_T may be calculated using (10a), (10b) and (10c). A useful linearisation for high tip speed ratios and a method of incorporating non-uniform induced velocity are given in Shankar (1976a). In figures 3a and 3b computations based on the performance analysis are compared with the experimental results of South & Rangi (1972). It may be seen that the agreement is generally satisfactory. Thus, the analysis is a useful tool for the design of Darrieus rotors.

3. Curved bladed turbine

In order to gain direct experience in the design, construction and operation of VAWTs it was decided in 1975 that a turbine be built at NAL. At the outset it was decided that simplicity, availability of materials and speed of fabrication would be the most important considerations. The design did not therefore take into consideration the problems that might arise in mass production; nor was economics considered except in so far as to avoid unnecessary or wasteful expenditure.

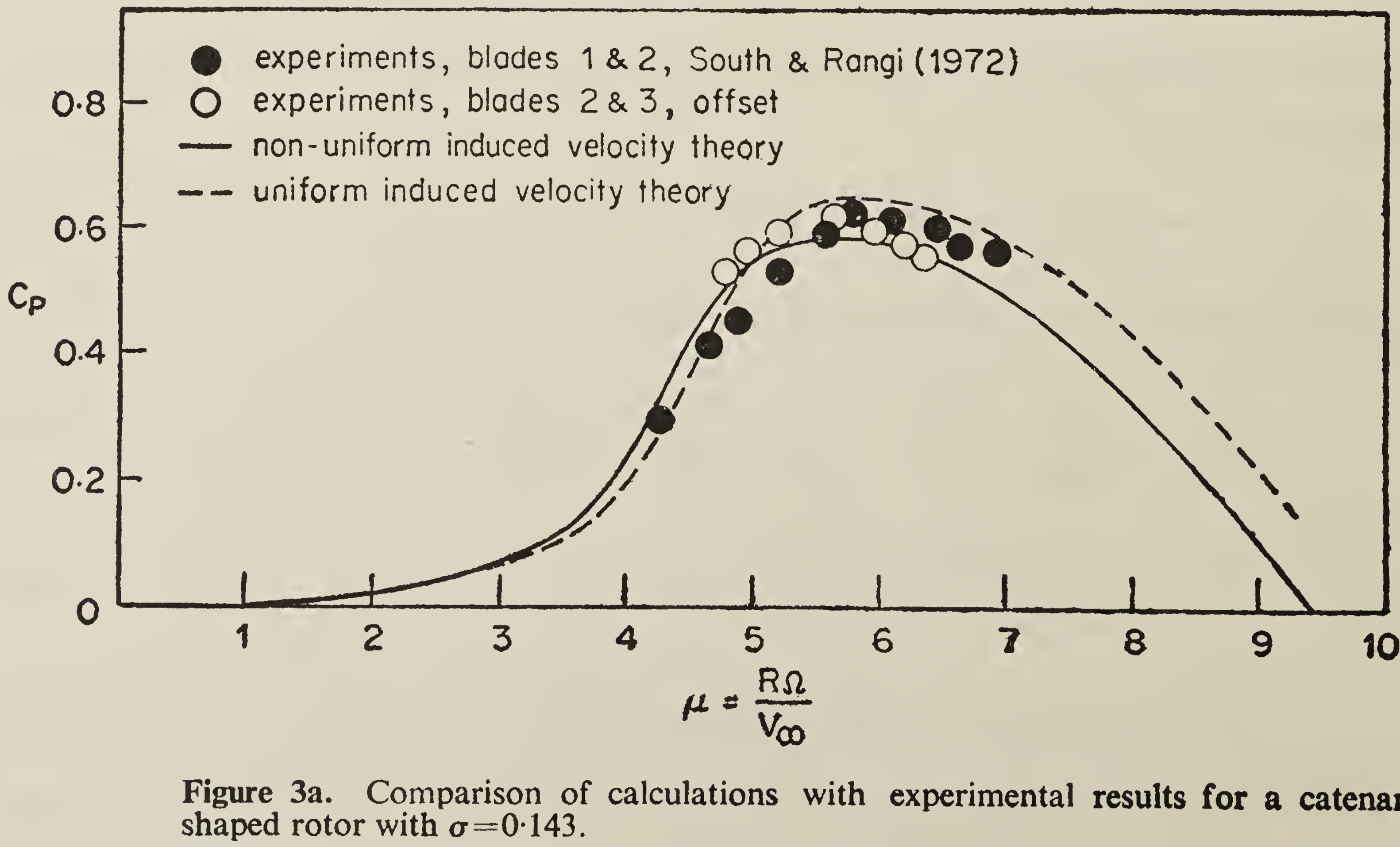

Figure 3a. Comparison of calculations with experimental results for a catenary-shaped rotor with $\sigma=0{\cdot}143$.

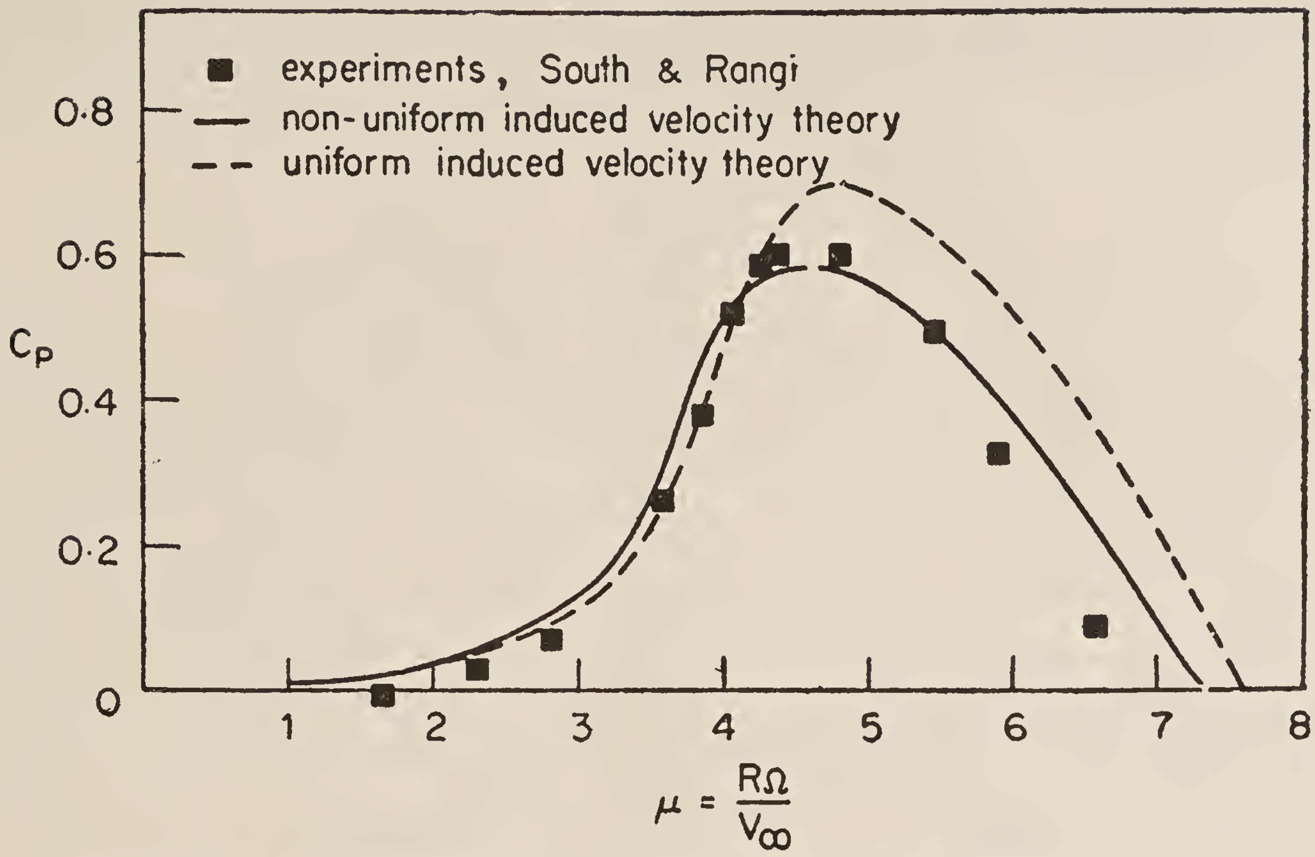

Figure 3b. Comparison of calculations with experimental results for a parabolic rotor with $\sigma = 0{\cdot}25$.

Aerodynamic performance calculations led to the following specifications (Shankar 1975).

Power output	1000 W in winds of about 25 km/hr
Rev/min	135 at rated power and wind speed
Frontal area	17·2 m^2
Blade shape	Catenary of diameter 5 m and height 5 m
Number of blades	2
Aerofoil section	NACA 0012 of chord 250 mm
Starters	Two Savonius buckets of height 1 m and diameter 2 m.

Figure 4 shows a sketch of the turbine configuration and support system. The central column is a welded structure made of three 25 mm × 25 mm × 6 mm angles located at the vertices of an equilateral triangle of base 250 mm. The rotor is supported on a four-legged steel table with the table top 2 m above the ground. The central column rotates with the blades, the upper bearing being held in place by three 6 mm guy wires. A simple band brake assembly was used for emergency breaking, the assembly being located below the lower bearing.

The method of construction of the blades was as follows. Two steel tubes, approximately 13 mm in diameter were bent to the shape of the catenary. A wooden former also of the same shape was erected so that the blades could be built on the former. Now wooden pieces, approximately 25 mm thick, were roughly shaped to the aerofoil profile. These pieces had two slots, 13 mm wide, cut out equidistant from the quarter chord point and spaced 52 mm apart. The wooden pieces were assembled on the former, the steel tubes placed in the slots, and the wooden pieces glued together. The outer surfaces were then finished to the aerofoil profile. The blades were then finally finished with fibreglass cloth (for weather protection and extra strength), smoothed with putty and painted.

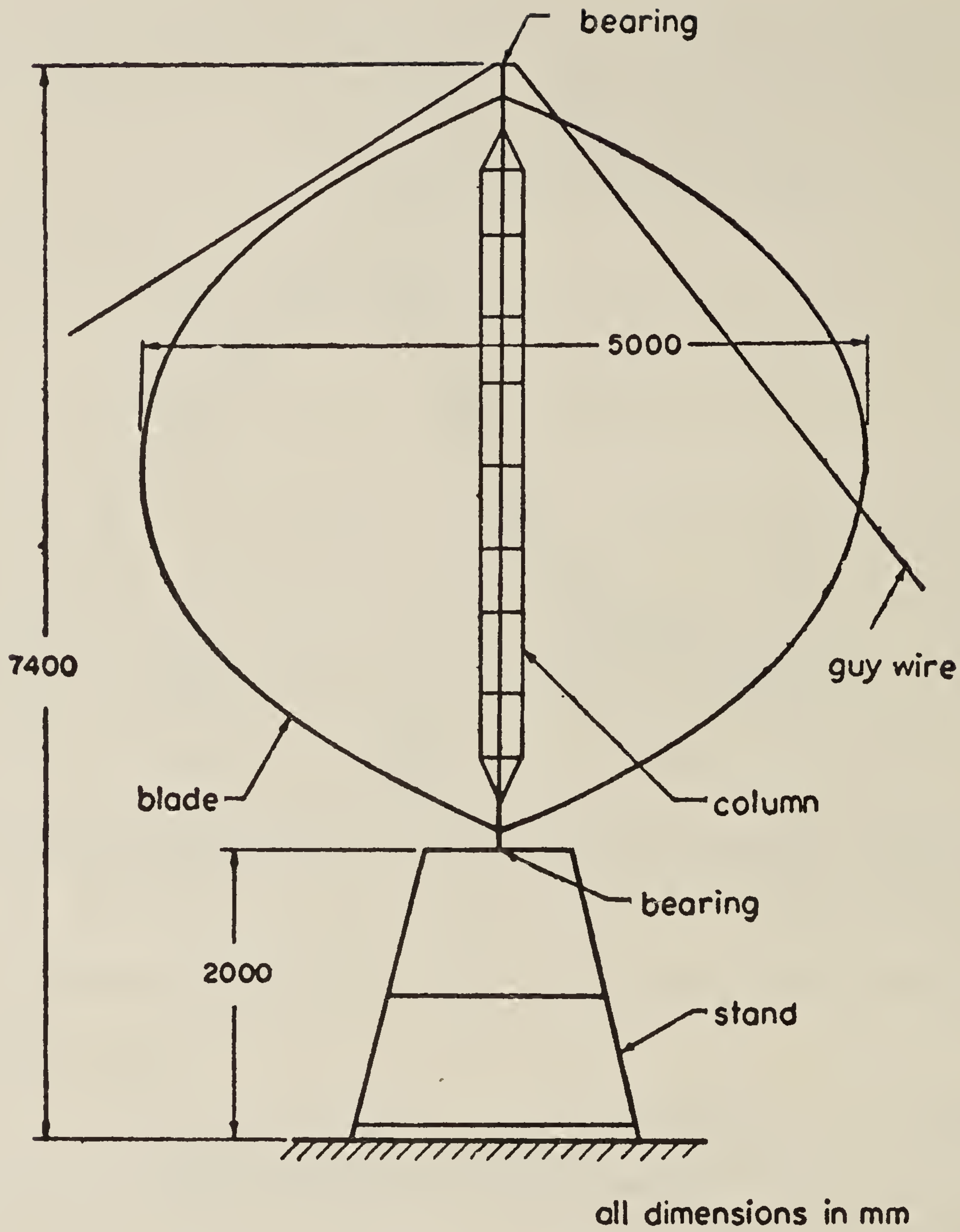

Figure 4. Sketch of the wind turbine configuration and support system.

The turbine was used to drive a commercially available self-priming centrifugal pump rated at 1 h.p. at a shaft speed of 1440 rev/min. A 9·3:1 step-up gear box using chain and sprockets was used for shaft speed matching. The choice of the load was poor as the commercial pump requires high starting torque and is very inefficient. In fact a separate d.c. motor was used for on-load starting purposes.

Figure 5 (plate 1) shows a photograph of the VAWT. Details of the findings of the initial tests are given in Shankar (1975). In summary it was found that:

(i) the turbine did generate 1 kW and more in winds of 25 km/hr and above;

(ii) the turbine was not self-starting on load. With the 2 m diameter Savonius buckets, self-starting on no load occurred in winds of about 10 km/hr;

(iii) the turbine-bearing system, which consisted of a 7211 angular contact bearing (55 mm i.d.) at the bottom and a 1205 self-aligning bearing (25 mm i.d.) at the top, had a high starting frictional torque of the order of 1.5 kg. m. The estimated total vertical load in this configuration was between 300 and 400 kg;

(iv) the conventional centrifugal pump is not suitable for this type of turbine.

Following the initial tests various modifications were considered and implemented. A configuration having the central column stationary was tried out (figure 6, plate 2). A clutch assembly was designed and fabricated which permitted the rotor blades to be off-load at start and to engage the load only when the rotor rev/min was around 70. The device used the centrifugal load of the blades to lift a friction pad concentric to

the shaft; initially the pad was free but at around 70 rev/min its vertical movement forced it to engage the load. This configuration was found to be superior to the initial one used as far as starting characteristics are concerned.

4. Wind tunnel tests of Savonius rotors

The Savonius rotor is a vertical axis device which has a high starting torque and reasonable peak power output. Its use as a windmill has been restricted till now because of the large surface area it employs. However, there has been renewed interest in this device in view of its simplicity. Using cloth-like surfaces it now appears that Savonius windmills may have potential in regions of low mean wind speed for generating small amounts of power for water pumping etc. (see Govindaraju & Narasimha 1977, 1979). At NAL, interest in the Savonius rotor stemmed from its use as a starter for the Darrieus rotor. In view of the negligible amount of reliable data on Savonius rotors it was decided to test a range of configurations in the Boundary Layer Tunnel at NAL.

Both two-bladed and three-bladed geometries were tested. Figures 7a and 7b show the configurations that were tested. The models, made of 1 mm aluminium sheets, were of diameter 200 mm and height 70 mm. The models were tested in the open jet of a wind tunnel of rectangular section of dimensions 1·51 m×0·305 m. Thus the blockage of 3% was quite small. Tests were carried out at wind speeds ranging from 7·6 m/s to 15·2 m/s and model rev/min ranged from 0 to 2300.

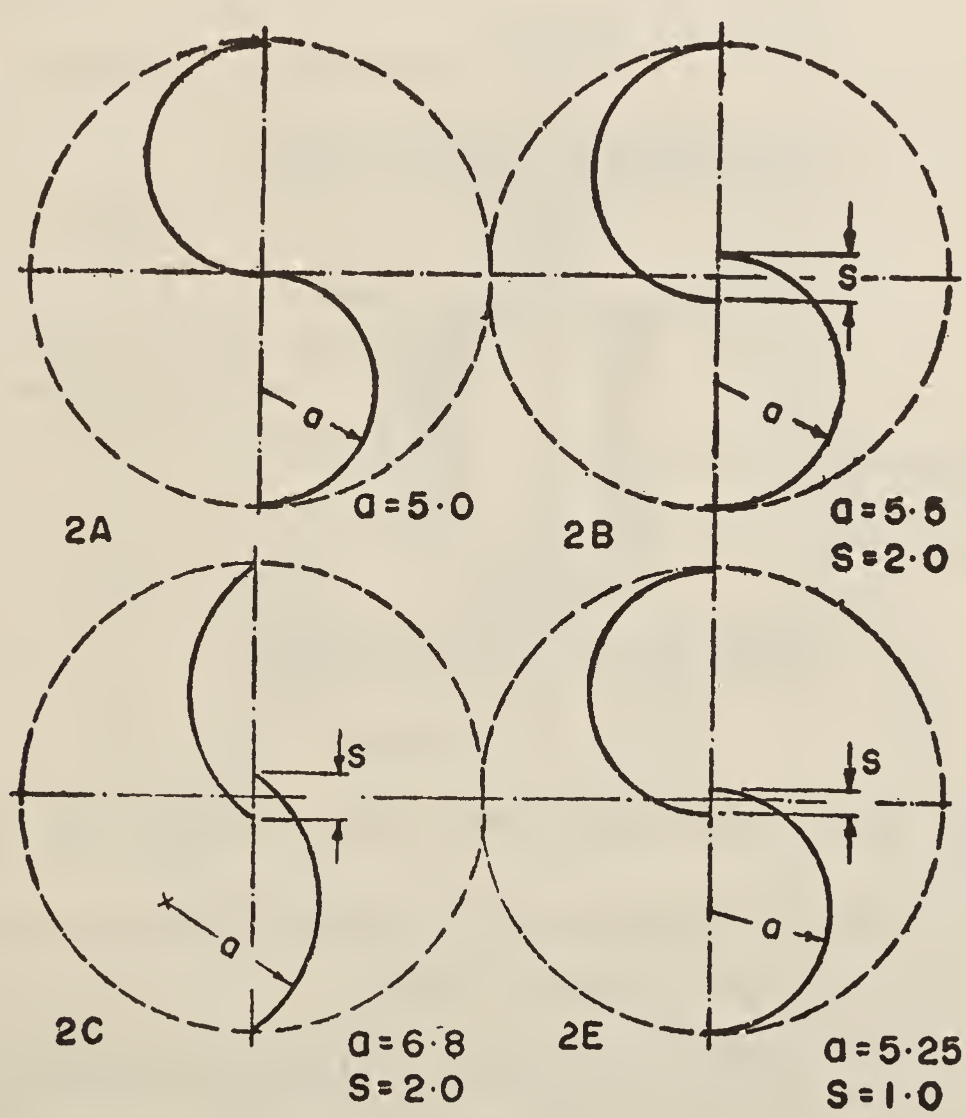

Figure 7a. The geometrical characteristics of two-bladed Savonius rotor models; $d=20$ cm.

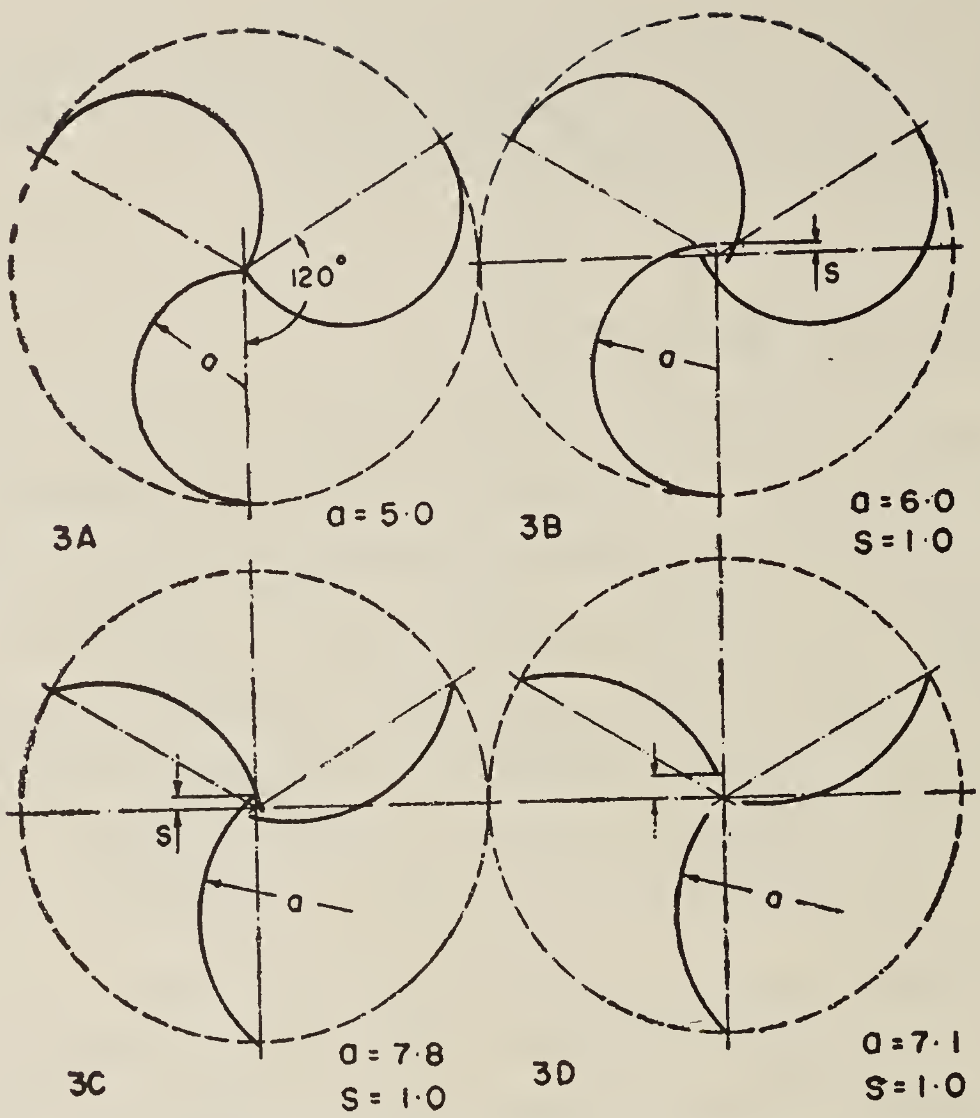

Figure 7b. Geometrical characteristics of three-bladed Savonius rotor models; d=20 cm.

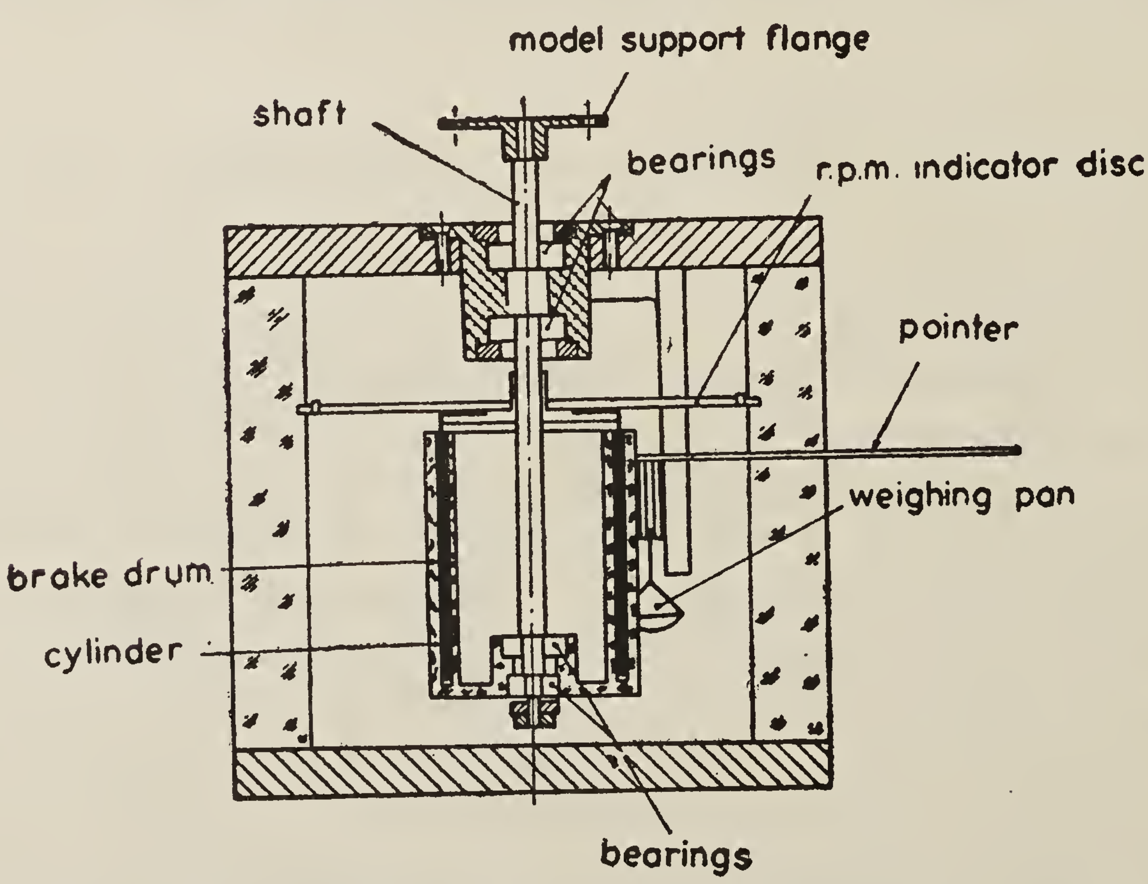

Figure 8. Sketch of the viscous dynamometer used in the wind tunnel experiments.

The balance used was a viscous dynamometer and is sketched in figure 8. Details of the dynamometer are given in Shankar (1976b).

Figures 9a and 9b show the measured variation of power coefficient C_P with tip speed ratio μ for the two-bladed and three-bladed models. It is clear that the two-bladed rotors generally have much higher peak power output than the three-bladed rotors. The significant findings of the tests were

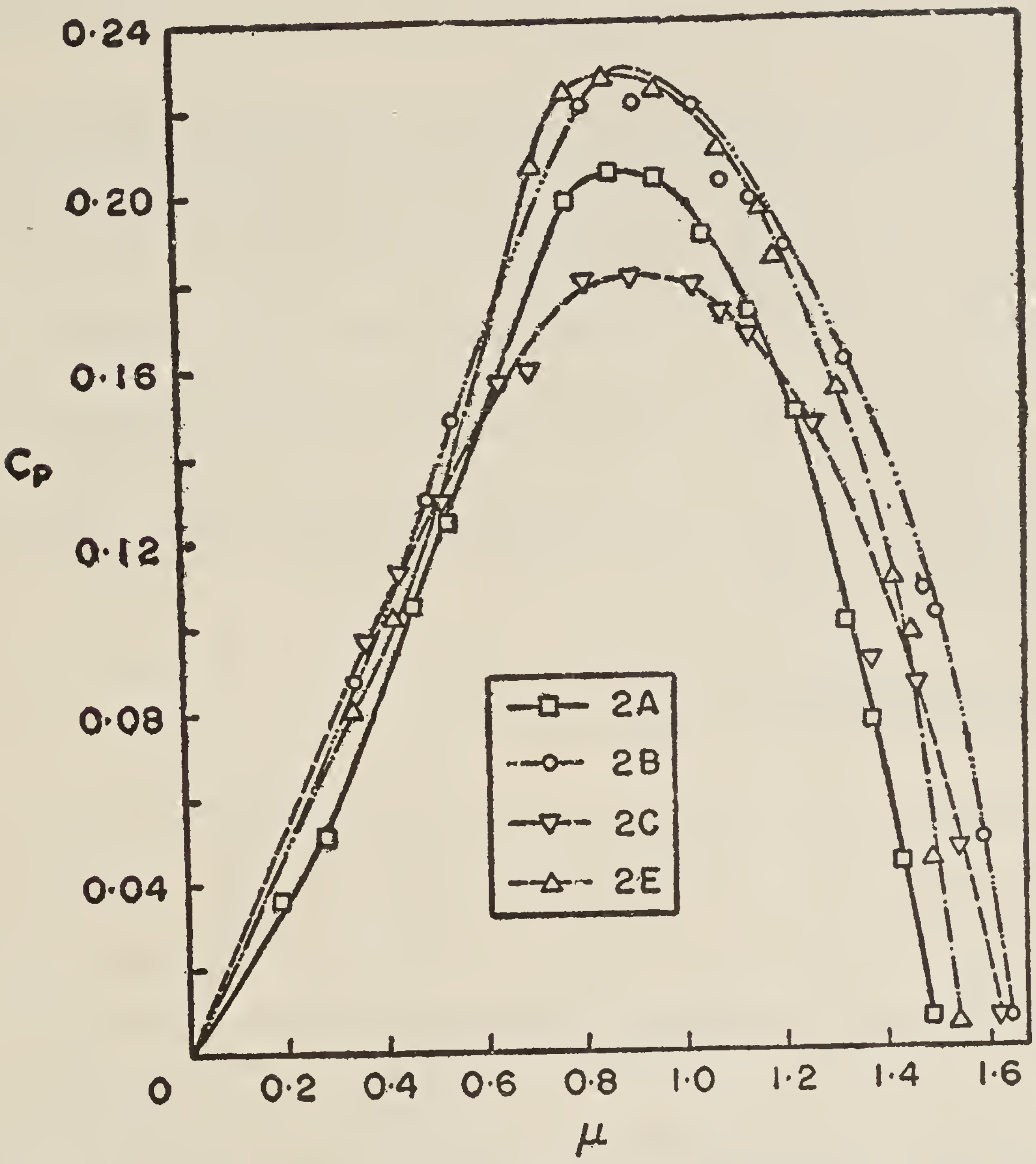

Figure 9a. Power coefficient for two-bucket models at a Reynolds Number of $1{\cdot}96 \times 10^5$.

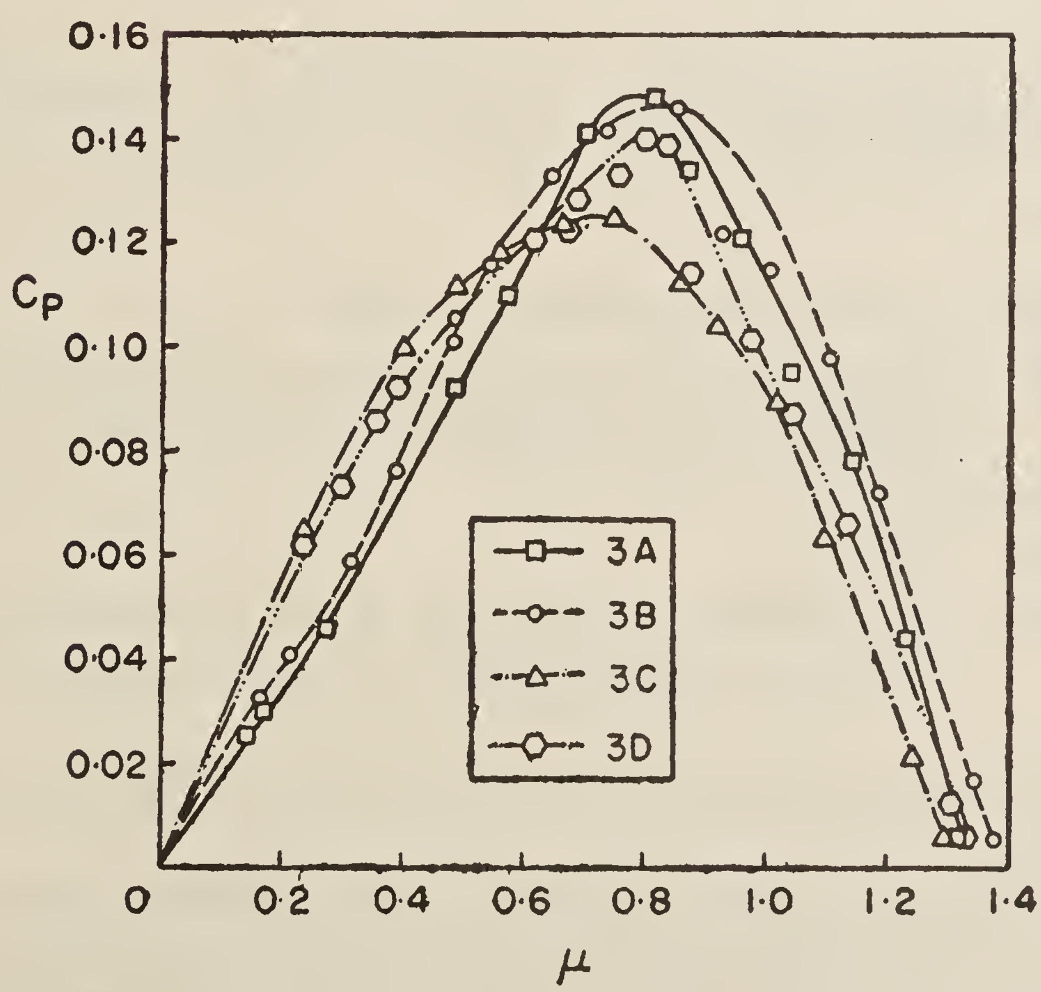

Figure 9b. Power coefficient for three bucket models at a Reynolds Number of $1{\cdot}96 \times 10^5$.

(i) in the range of Reynolds Numbers tested, the performance of all Savonius type rotors improved with Reynolds Number;

(ii) two-bladed Savonius rotors have almost 50% higher peak power output than the three-bladed rotors;

(iii) three-bladed rotors have smaller regions of negative starting torque but the torque coefficient at start is not significantly larger than that for two-bladed models;

(iv) while gap size is of some significance for the two-bladed models it is not of much significance for three-bladed models;

(v) shallow bucketed models have higher torque at low tip speed ratios but have worse peak performance;

(vi) a support rod at the centre of a Savonius rotor with a gap does not significantly affect its performance.

Most of the above findings have been confirmed in tests done at the Sandia Laboratories by Blackwell *et al* (1977).

5. The straight bladed turbine

A great disadvantage of the Darrieus rotor is the complication inherent in the fabrication of the curved blades. The large curved blades also pose a problem in handling, transportation and assembly. The main reasons for using curved blades are structural. The curved blade minimises bending stresses and the attachments to the top and bottom of the central shaft help to minimise vibrations. However, the possibility of using straight blades has remained an intriguing one over the years.

At NAL, a decision was made to try out a turbine using straight blades. At the outset it was decided that, in order to limit bending stresses and centrifugal loads, the upper rev/min would be strictly limited. The blades too would be of minimum weight.

Figures 10a (plate 3) and 10b (plate 4) show photographs of two- and three-bladed versions of the straight-bladed turbine. The blades were fabricated out of aircraft quality aluminium sheets with internal stiffeners. The specifications of the turbine were as follows.

Power output	1 kW in winds of speed 25 km/hr
Shaft speed	80 rev/min for the two-bladed and 70 rev/min for the three-bladed version at rated power and wind speed
Frontal area	17 m^2
Blade length	2·44 m
Blade profile	Conforming to NACA 0024 section of chord 0·44 m
Starters	2 Savonius rotors of height 1 m and diameter 2 m

The 24% thick section and the large chord were used to minimise bending stresses in the sheet metal.

While the turbine pick-up, starting friction and general performance were found to be satisfactory it was found that the support system was inadequate especially at revolutions greater than 100 rev/min. It has been our experience both with the straight-bladed turbine and the curved-bladed one that guy wire supports are really not adequate. In any practical system the upper bearing must be housed in a rigid structure.

6. Conclusions

The development work done at NAL gave us experience in the design, fabrication and field testing of Darrieus turbines. There is no doubt that the Darrieus rotor is a high speed device of efficiency comparable to horizontal axis windmills. It seems likely that this device will find use in the conversion of wind energy to electric power especially if used on a large scale in conjunction with the grid. In fact a 200 kW turbine driving a generator is at present being tested in Canada. With such large devices it is quite feasible to have adequate control systems for starting and controlling the system. In India, however, the mean wind speeds are generally so low that it is unlikely that wind power can be economically converted to electric power for grid augmentation. The most practical use for wind power is likely to be direct water pumping for drinking water and minor irrigation purposes. The water pumping application generally implies high starting torque and low control costs. Hence it appears, at least from the NAL experience, that Darrieus turbines are not likely to be of much use in the Indian context.

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Plate 1

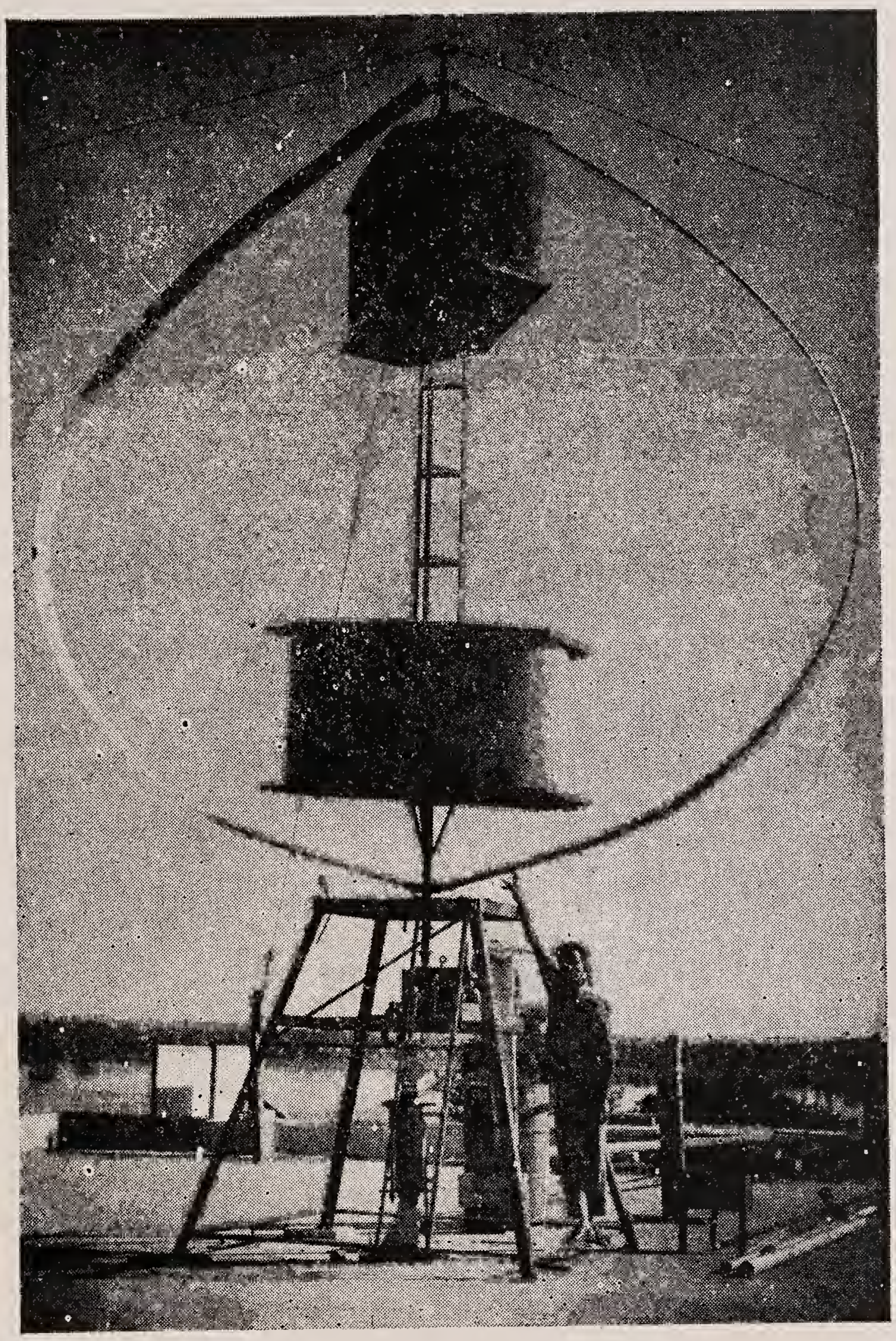

Figure 5. Photograph of curved bladed VAWT with two blades.

Plate 2

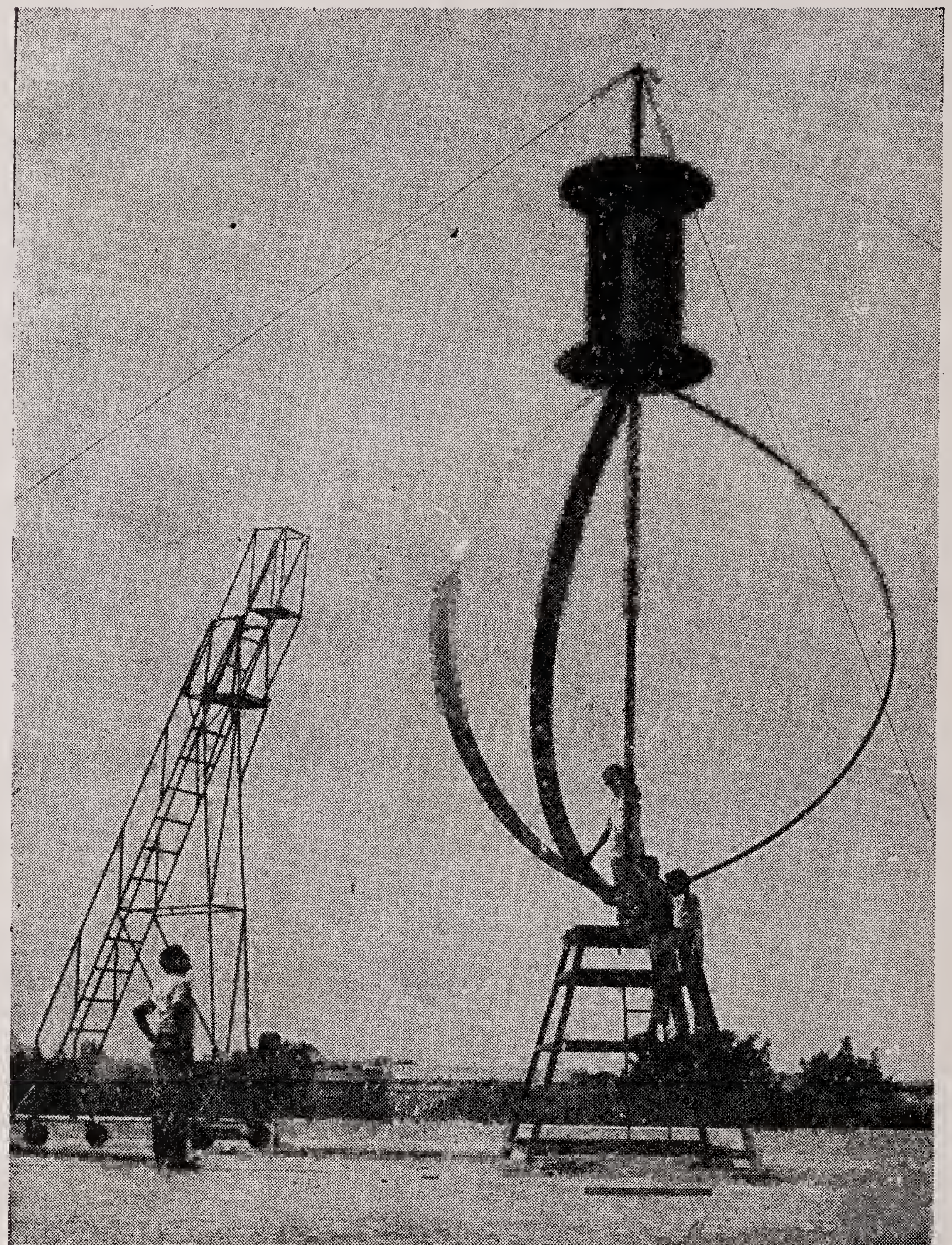

Figure 6. Photograph of three-bladed turbine using a stationary central column and with clutch assembly at the base.

Plate 3

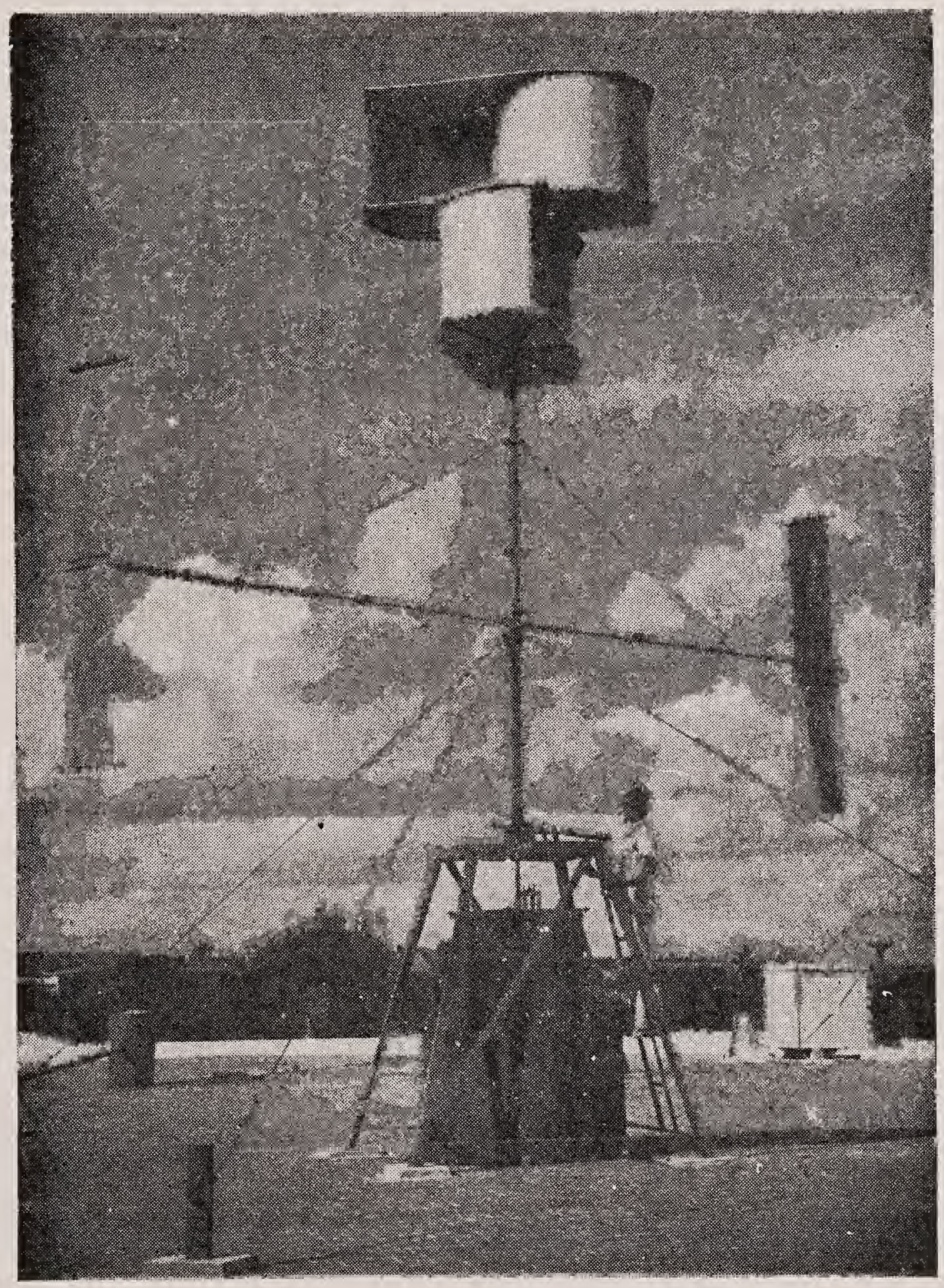

Figure 10a. Photograph of the straight-bladed turbine with two blades.

Plate 4

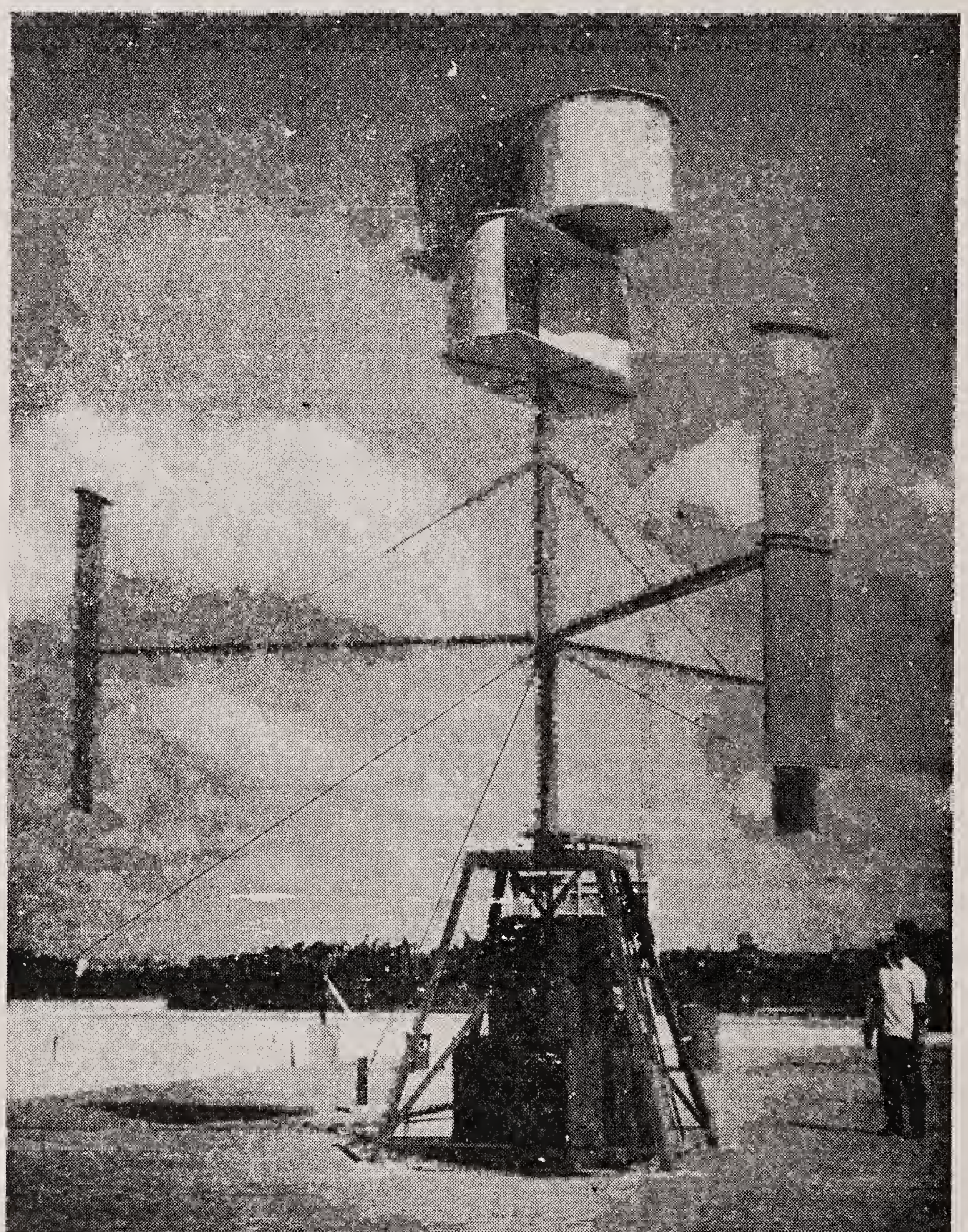

Figure 10b. Photograph of the straight-bladed turbine with 3 blades.

A low-cost water pumping windmill using a sail type Savonius rotor

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Abstract. A water pumping windmill which can be built largely with materials and skills available in rural areas has been designed and fabricated. The windmill uses a Savonius rotor and incorporates a novel sail-type construction. The pump is of a positive displacement type using the casing of a pneumatic tyre for the pumping chamber. Two prototypes have been constructed and these have indicated a reasonable performance and reliability.

Keywords. Windmill; Savonius rotor; water pump; low cost technology.

1. Introduction

For centuries wind energy has been exploited in many parts of the world, but to this day windmills are a rare sight in India. In the 1950s and early 1960s, the National Aeronautical Laboratory tried vigorously to introduce windmills into India by erecting more than sixty windmills of the horizontal axis, multi-bladed type in various parts of the country (Sen Gupta 1966), but they have not gained acceptance.

An important reason for this lack of interest in wind energy must be that winds in India are relatively low and vary appreciably with the seasons. For example, data quoted by Ramakrishnan & Venkiteshwaran (1961) indicate that during November about half the country experiences mean winds of less than 5 km/hr and almost nowhere are they higher than 20 km/hr; during July, on the other hand, more than half the country has mean winds exceeding 15 km/hr, and about a sixth has wind speeds higher than 20 km/hr. These low and seasonal winds imply a high cost of exploitation of wind energy. Calculations based on the performance of a typical windmill (Sivaraman & Venkiteshwaran 1963) have indicated that a unit of energy derived from a windmill will be at least several times more expensive than energy derivable from electric distribution lines at the standard rates, provided such electrical energy is at all available at the windmill site.

The above argument is not fully applicable in rural areas for several reasons. First, electric power is not and will not be available in many such areas due to the high costs of generation and distribution to small dispersed users. Secondly, there is a possibility of reducing the cost of the windmills by suitable design. Lastly, on small scales, the total first cost for serving a felt need and low maintenance costs are more important than the unit cost of energy. This last point is illustrated easily: dry cells

provide energy at the astronomical cost of about Rs 300 per kWh and yet they are in common use in both rural and urban areas.

This raises the question of what the felt needs are that a windmill might satisfy. While large scale energy production at some favourable sites in India is a possibility that needs to be explored, there appears to be a definite need for small sources of mechanical energy in rural areas. For example, even casual polls among villagers quickly reveal that their first concern is invariably water—for drinking, washing and irrigation; and lifting water is a task which a windmill can perform. For such a task, a windmill should produce about 100 W, considering that a pair of bullocks, often used for lifting water in villages, typically provides about 250 W power.

These considerations define the problem of designing a windmill for use in rural India: it must work efficiently at relatively low winds in the 10–20 km/hr range and must provide about 100 W typically. For individual ownership to be possible, it must have a low first cost (closer to Rs. 10^3, which is the cost of a pair of bullocks, rather than around Rs. 10^4 which is the cost of currently available windmill designs), and it should be simple and easy to build and maintain.

This paper describes one design that appears to meet these requirements and to merit further study.

2. Design principles

The requirements set out above appear to be best satisfied by a design that can utilise an appropriately low technology; the principles that characterise such technologies have been set out at length by Reddy (1975). In general, such a design should be labour- rather than capital-intensive, and use local materials and skills to the fullest possible extent. This suggests wide use of wood and fabric, both of which have been handled with considerable skill in Indian villages for ages and can be worked easily using handtools. Sophisticated controls and safety devices of the kind suggested for high technology windmills are obviously out of place in such a design. Thus, the windmill should start and operate reasonably well without attention and should have simple safety devices built into its design. Any maintenance or repairs that may be needed should be within the skill of the villagers themselves.

The use of such a low technology calls for a change in the engineer's usual attitude to design. Materials in their natural state exhibit large variations in dimensions as well as other properties, and it is not possible to adapt them to a standard design with fixed dimensions unless one processes them—and this calls for a technology which is, in general, energy-intensive and is therefore to be avoided as far as possible. Thus, for example, the windmill should use available timber even avoiding conversion to standard sizes wherever possible. This implies that a large number of design details (joints, location and type of fixtures for support of bearings etc.) will have to be determined by the quality and type of timber available. But such a design should still incorporate sound engineering in the sense that it should develop the necessary performance at the least possible cost. We may call this approach 'soft design'—something that is sound in principle but adaptable to local circumstances with modest variations in dimensions, materials and skills. Bullock carts and traditional housing are examples of such design.

Use of the soft design approach imposes certain constraints on admissible design solutions in any specific context. For example, a windmill using aerofoil blades demanding precise blade forms and excellent surface finish is inconsistent with the concept. This is so not because of any inherent limitations to attainable precision. A look at the carvings in ivory and metal made by the cottage industries in India will convince one of the extreme precision attainable. But such precision is achieved at enormous labour cost and will be uneconomical.

It is not obvious that satisfactory design solutions consistent with the above principles always exist. What follows is the description of one attempt to find such a solution for a device that could extract wind energy in sufficient quantity to make a significant contribution to energy use in rural areas.

3. The Savonius rotor

A horizontal axis windmill rotor requires mounting on a turntable or equivalent for orienting it into the wind at all times. This complexity is avoided in a vertical axis windmill which was therefore considered more suitable for rural application.

Among vertical axis machines the Darrieus rotor has good aerodynamic efficiency but suffers from poor starting torque, and, without complex starting devices, is unsuitable for pumping water. Further, the rotor is not easily constructed or maintained using low technology.

Windmills operating solely on drag differences (like the cup anemometer) usually have such poor efficiency that they tend to be uneconomical.

The Savonius rotor, invented around 1930, has moderately good efficiency and a satisfactory starting characteristic, the latter being particularly important for use with a positive displacement pump. A small windmill for pumping water was in fact designed by the Brace Research Institute (Anon 1973) many years ago using halves of oil drums for rotor buckets. Though this work indicated that a moderate efficiency of about 15% was attainable by such a rotor, the windmill itself was too small to be generally useful. Being related to the sizes of oil drums, the above rotor cannot be easily scaled up. It was therefore decided to design a rather larger windmill using fabric for the rotor surfaces.

Some wind tunnel experiments (Govinda Raju *et al* 1976) were first conducted on small Savonius-type rotors of 100 mm diameter to study the effect of the end plates and the bucket shape on performance. The results of some other test programmes on this class of rotors have also recently become available (Shankar 1976, 1979; Manser & Jones 1976; Blackwell *et al* 1977).

To test the feasibility of sail-type construction a windmill of about 0·2 m^2 sail area was first fabricated. Here, the sails were supported by wires strung between end plates fixed to the shaft. Tests in the 14 ft $\times$ 9 ft wind tunnel at the Indian Institute of Science showed that the scheme was feasible and gave satisfactory performance.

Two windmills, designated prototypes 1 and 2 respectively, each of roughly 8 m^2 projected sail area, have since been designed and fabricated. They are largely similar, but prototype 2 uses a slightly different sail profile and rotor support structure. The descriptions to follow apply to both with the differences noted.

4. Support structure for the rotor

Each windmill consists of two A-frames spaced apart by two connecting beams with the rotor supported between the beam centres. The lower parts of the A-frames are triangulated by diagonal members. Guy wires are used to add strength and stiffness to the structure. Figure 1 (Plate 1) and Figure 2 show the details of prototype 2. Both prototypes utilise the same structural concept, but the sizes of members are different. The first prototype used cut timber of 5 cm × 10 cm nominal size and boards of 2·5 cm nominal thickness. The second prototype uses casuarina poles. These poles were obtained by felling and trimming standing trees, purchased near the erection site. The trees were 20 to 25 cm diameter near the base tapering to about 15 cm diameter at a height of 10 m. All joints in wood are by mild steel bolts of 12 mm diameter. The guy wires are made of galvanised mild steel of a commercial grade.

The support structure receives the forces exerted by the rotor at its bearings. These forces have a significant periodic component with the period corresponding to the rotational speed of the rotor. To avoid excessive vibrations, the natural frequencies of the structure must be sufficiently above the frequency corresponding to maximum expected rotor speed (around 100 rev/min). The observed frequencies of the structures were 160 cycles/min for prototype 1 and 250 cycles/min for prototype 2 and are thus adequately above the rotor revolutions per minute. (These frequencies were obtained by counting the resonant oscillations of the structure excited by pulling periodically on a length of rope tied to a suitable part of the structure.)

Experience shows that the natural frequencies of structures considered above are strongly dependent on the flexibilities at the joints between various members. The frequencies given above were obtained with good matching at the lap joints in the structure, the bolts and turnbuckles being tight. Looseness of bolts or guy wires reduces the frequencies alarmingly and hence due care is necessary in making joints and in keeping the bolts tight.

5. The rotor

The rotor, based on the Savonius type indicated in § 3, consists of a vertical shaft is the form of a galvanised steel pipe with suitable welded end fittings; the shaft is supported by a simple self-aligning brass bush at the top and by a ball bearing at the bottom. The bottom end of the shaft can carry a brake/power-take-off drum and an end-crank for driving a pump.

Near the ends of the shaft are welded fittings to which can be bolted wooden end plates of built-up construction using planks of 12 mm and spars and ribs of 25 mm nominal thickness. As shown in figure 3, these end plates each have a central structural part to resist loads exerted by wires strung vertically between them. Extensions to the central parts in the form of plywood sheets supported by ribs complete the end plates. Bamboo matting may conveniently replace the plywood sheets and this possibility will be tried in the future.

The wires strung between the end plates (16 in all) form the support system for the two sails of jute canvas which form the aerodynamic surfaces of the rotor. The wires

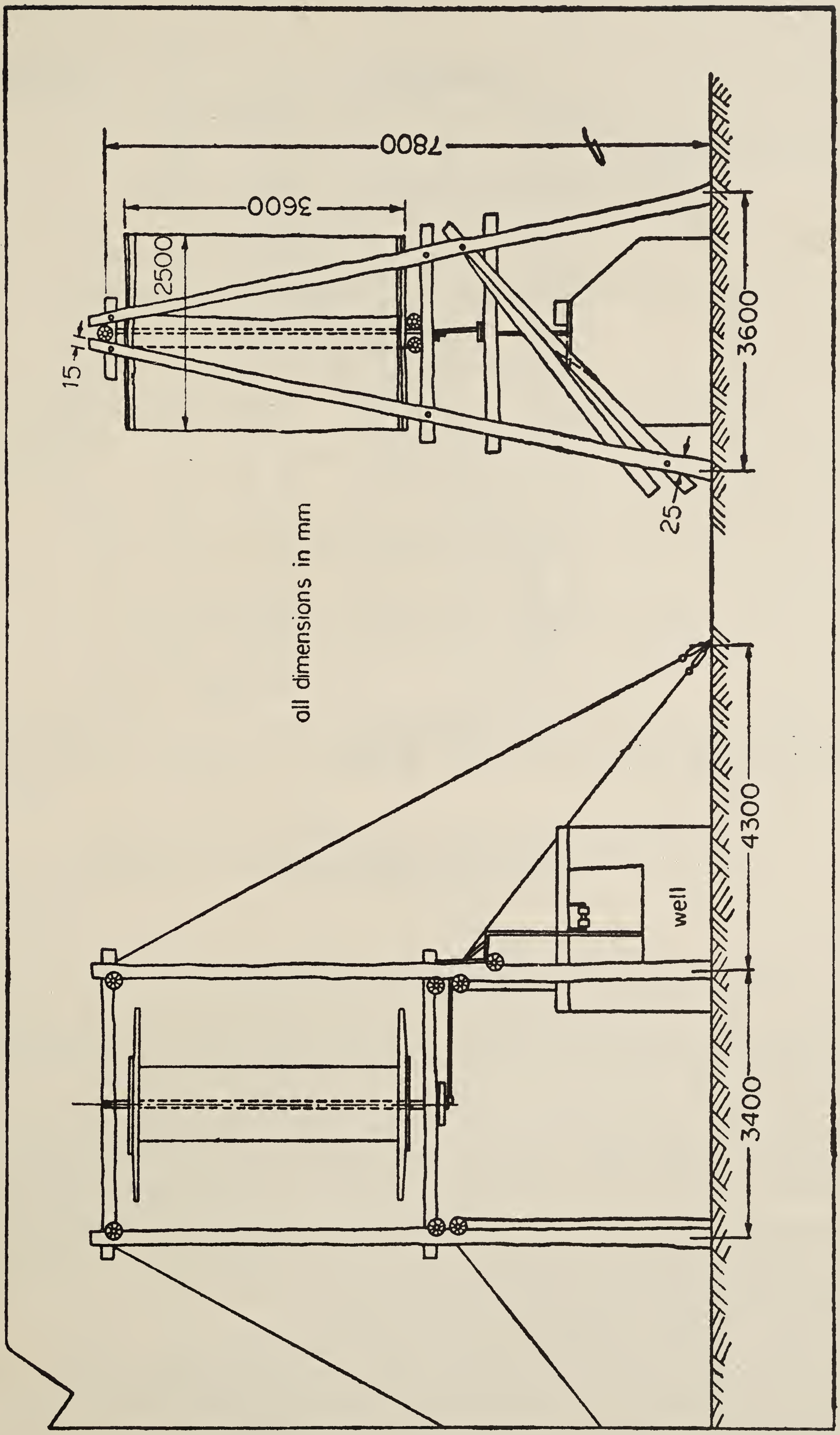

Figure 2. Configuration and major dimensions of prototype.

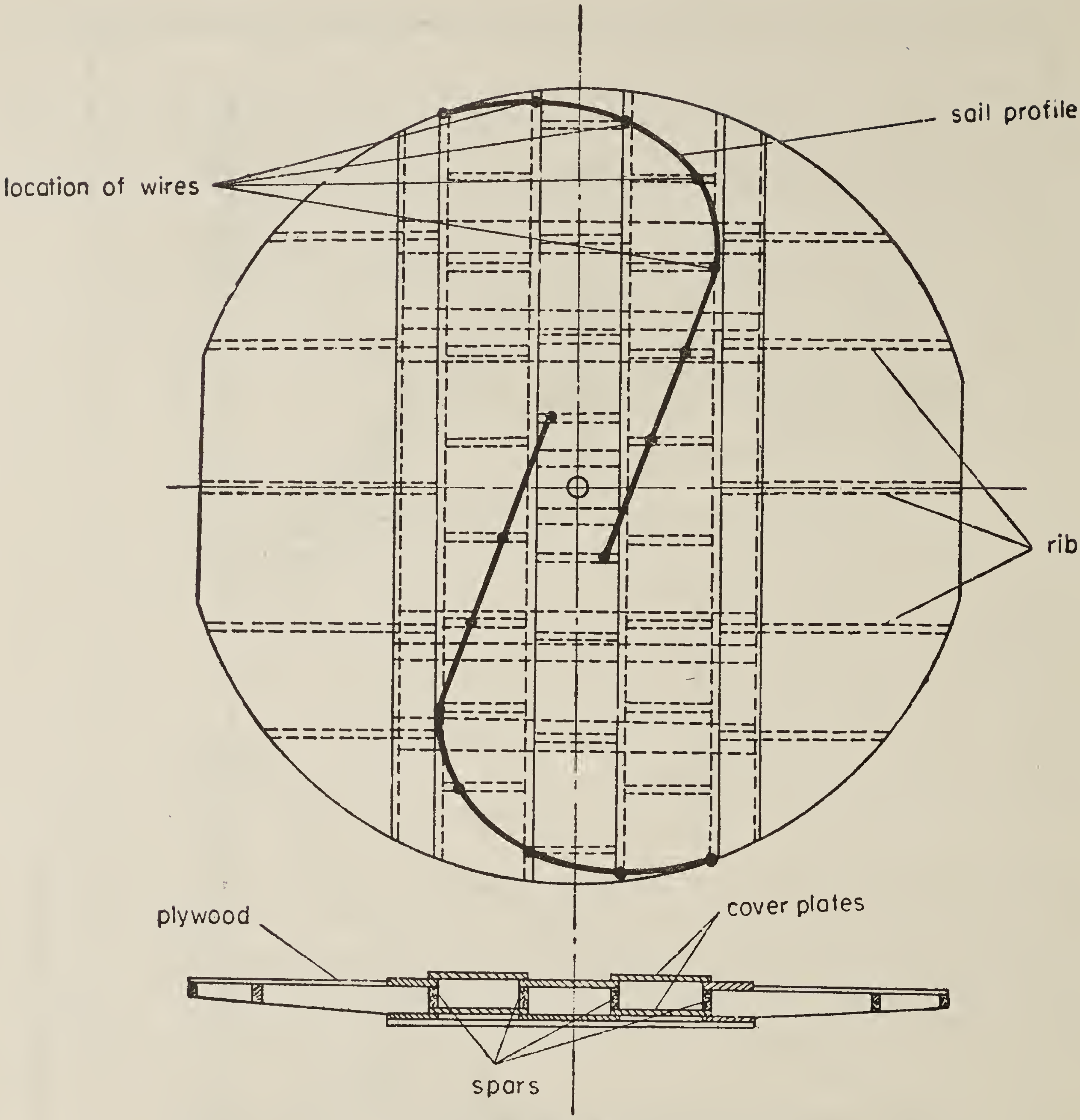

Figure 3. End-plate assembly, showing also sail geometry..

pass through ribs in the end plates from one side and are clamped on the other side. During installation, the wires are so clamped that there is a play at their midpoint of about 15 cm.

The sails of jute canvas are attached to the wires by threading the wires through loops stitched to the canvas. Each sail incorporates a total of five loops, four for the first four wires counting from the leading edge and the last one at the trailing edge. This leaves three wires touching but unattached to each sail. Skirts, about 10 cm wide at the edges near the end plates, provide a seal there and allow for any errors and/or shrinkage of the fabric after installation. After installation, the sails and skirts are painted with coal tar to make them weatherproof.

The above scheme of attaching sails to their supporting wires incorporates an important element of safety in excessive winds. The wires at the trailing edges of the sails incorporate twisted joints just below the top end plate as shown in figure 4. Each twisted joint unwinds at a definite and predictable tension in the wire and in the event of this happening in a high wind, the corresponding sail opens out, being in

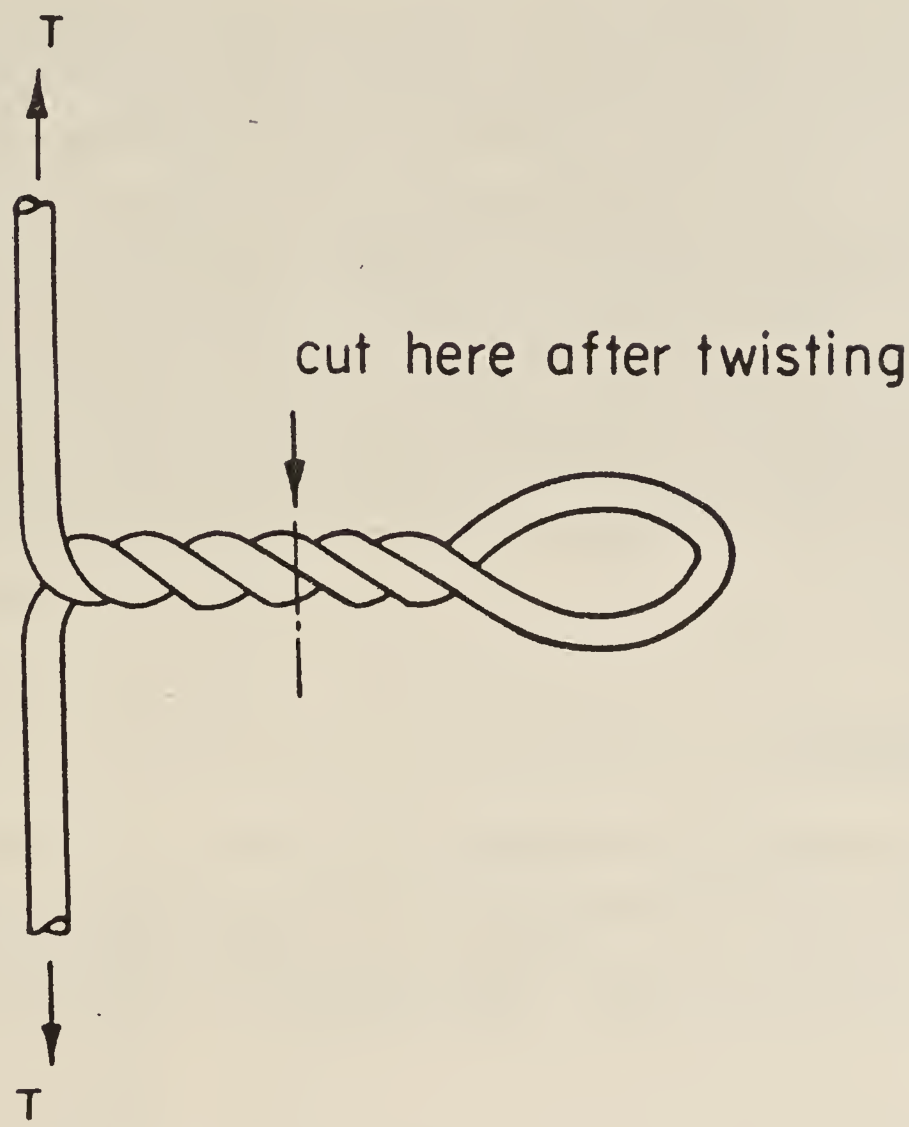

Figure 4. Safety wire.

that case held only by the four wires near the leading edges, thus reducing the rotor speed as well as unloading the structure. The scheme has worked well in actual practice.

6. The pump

One of the major uses of the windmill is expected to be lifting water from wells for domestic use or for minor irrigation. In such applications, the head against which water is to be lifted is generally 3 to 15 m with seasonal variations of 5 m. For this type of application only positive displacement pumps appear suitable because they can be directly coupled to the windmill and can be adapted to varying head conditions easily. It may be noted here that one or more of the well-known devices for lifting water (like the Archimedean screw, chain and bucket elevator, persian wheel etc.) can be used for this type of duty. But they appear non-competitive in comparison with the pump designed here.

Among the positive displacement pumps, the one suggested by Papanek (1972) appeared to be particularly suitable in the present context. The pump consists of the casing of a pneumatic tyre blocked by two discs (one at each bead) thus creating an enclosed volume. Relative displacement between the discs changes the enclosed volume and can be used as the pumping chamber of a positive displacement pump by adding a pair of non-return valves and pipes. Because the pneumatic tyres are generally designed for operation at an internal pressure of around 2 kg/cm^2 which corresponds to about 20 m of water, a pump using tyre casing can be used to pump against a head of up to this height.

Available pneumatic tyres range from about 35 cm in diameter for small scooters to more than a meter on heavy vehicles. These imply a pump displacement of about 1 litre per cm of stroke for the smallest tyre and progressively more for the larger sizes. The smallest tyre was found suitable for the present application and a pump using it is shown in figure 5 (plate 2) and figure 6. It is seen that the relative motion between the discs is imparted through a lever of ratio about 10 to bring the forces in the transmission between the windmill and the pump to a comfortable level.

For use with the windmill, the pump incorporates an unloading device in the form of a small leak and a check valve in the delivery pipe just after the delivery valve. This eases starting of the windmill as it reduces the torque demand of the pump at low rotor speeds.

7. The power transmission

The windmill power take-off point which is at the bottom of the rotor is typically 4 m above the ground level while the level of water in an open well is typically 10 m below ground level. The pump, whose suction is typically limited to 3 m, is thus to be located not much above water level. Horizontally, the windmill shaft is about 2·5 m

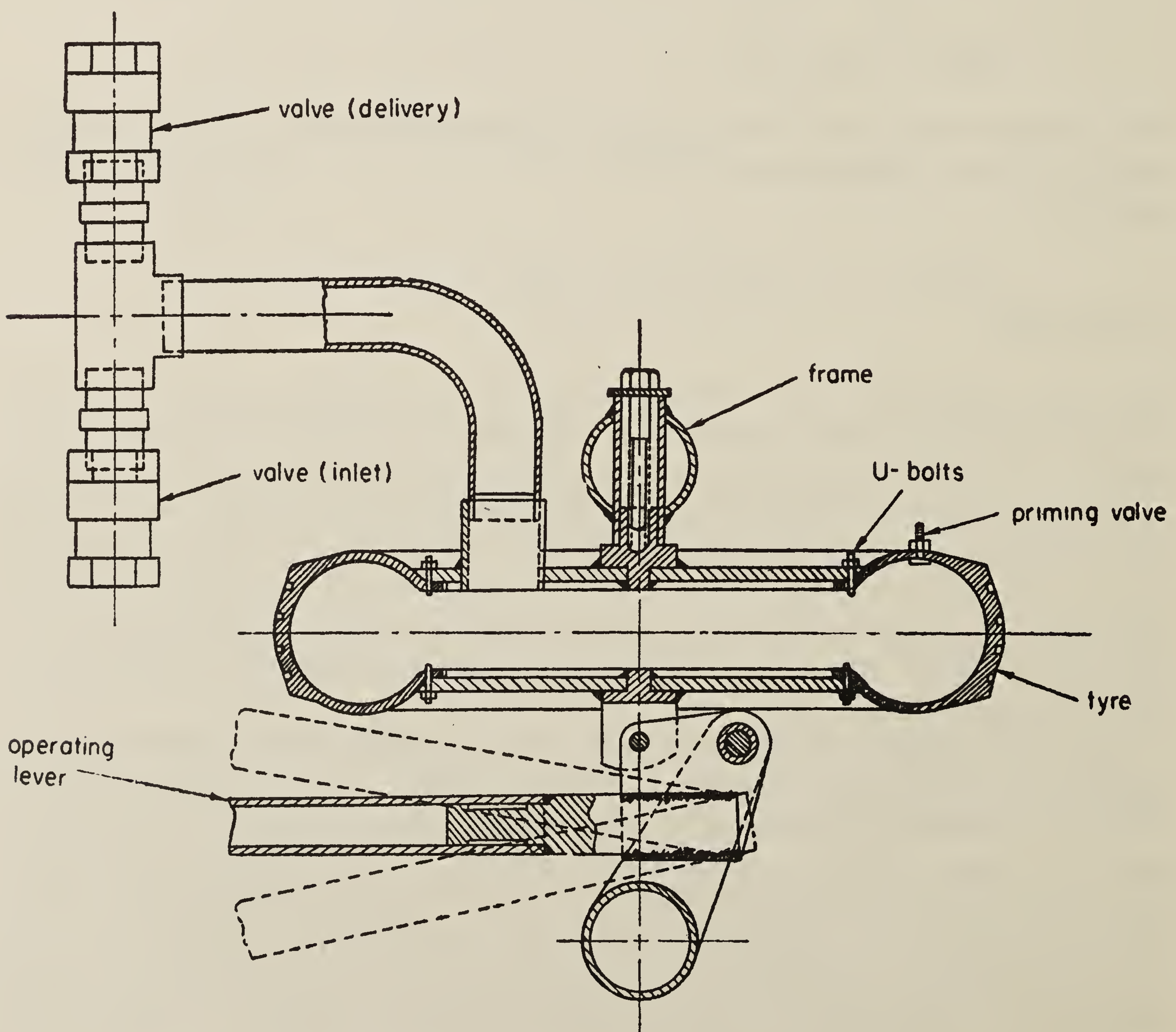

Figure 6. Cross-section of pump.

removed from the nearest point of the well. The transmission, which has to handle the problem of conveying power from the rotating shaft below the rotor to the oscillating pump operating lever at the pump, has thus to convey power over a distance of 15 m or more.

The transmission adopted is schematically shown in figure 7. It consists of a variable arm end crank at the shaft and a bell crank at a position vertically over the pump operating lever and horizontally at the level of the end crank. A connecting rod, with a ball bearing at one end and a ball-joint at the other, connects the end crank and the vertical leg of the bell-crank. An operating rod (roughly 11 m long in the second prototype), in the form of a GI pipe of 12 mm nominal size, connects the horizontal leg of the bell crank and the pump lever. Two supports, in the form of wooden blocks with holes drilled for the passage of the rod, are located at two points along the operating rod to prevent induced oscillations and /or buckling of the operating rod. Also, it is arranged so that the delivery stroke of the pump corresponds to a tensile load on the operating rod so that compression in the rod (corresponding to suction) is small.

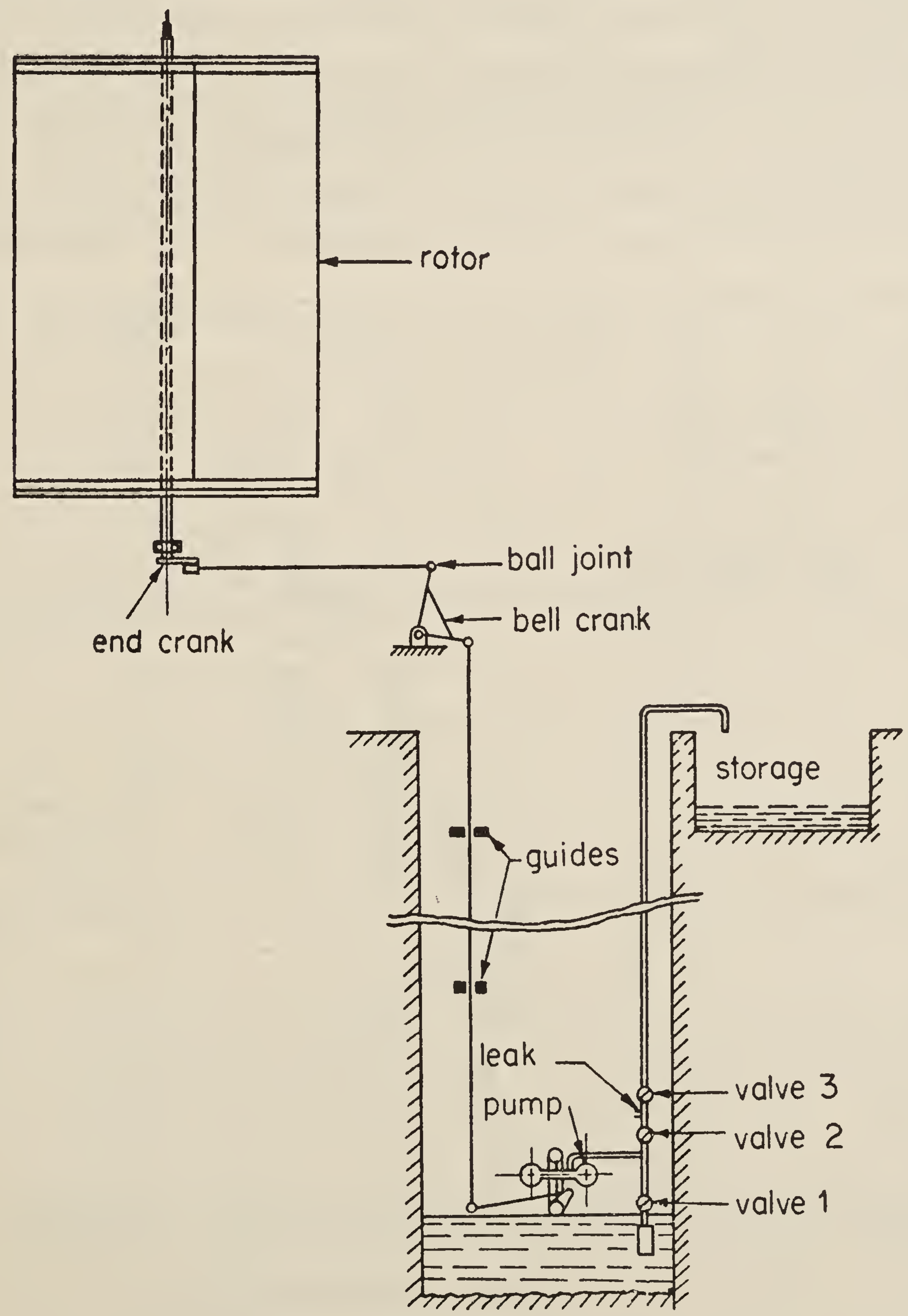

Figure 7. Schematic layout of wind-pump at Ungra.

8. Performance

The performance of a windmill-pump system depends on the individual characteristics of the windmill and the pump. The characteristics of a positive displacement pump can be analytically worked out to fair accuracy using data on hydraulic losses (Davies 1969). The characteristics of Savonius-type rotors are known fairly accurately and it is possible to estimate the performance of the wind-pump for any given combination of wind, head of water and pump displacement.

Such estimates of performance of the wind-pump of present design indicate the following. For a given head of water and pump displacement, there is a minimum windspeed below which steady operation is not feasible. As the wind speed rises above this value, the rate of water pumped increases rapidly at first and more slowly later. The efficiency of the system (defined as the ratio of the useful power delivered in lifting water to the power available in the wind crossing the rotor) is zero below the minimum speed, rises rapidly with further increase of wind-speed, reaches a maximum and then decreases monotonically. Thus it is possible to extract energy from the wind efficiently only over a narrow band of wind-speeds; and therefore careful adjustment of the pump displacement (i.e. stroke) is needed to maximise the water delivered for any given wind spectrum. For this reason, the present design incorporates a variable arm crank at the windmill to facilitate changing the pump stroke, which may be done from time to time to cater to changing wind and/or head of water. Figure 8 shows the performance of the first prototype windmill as estimated and as

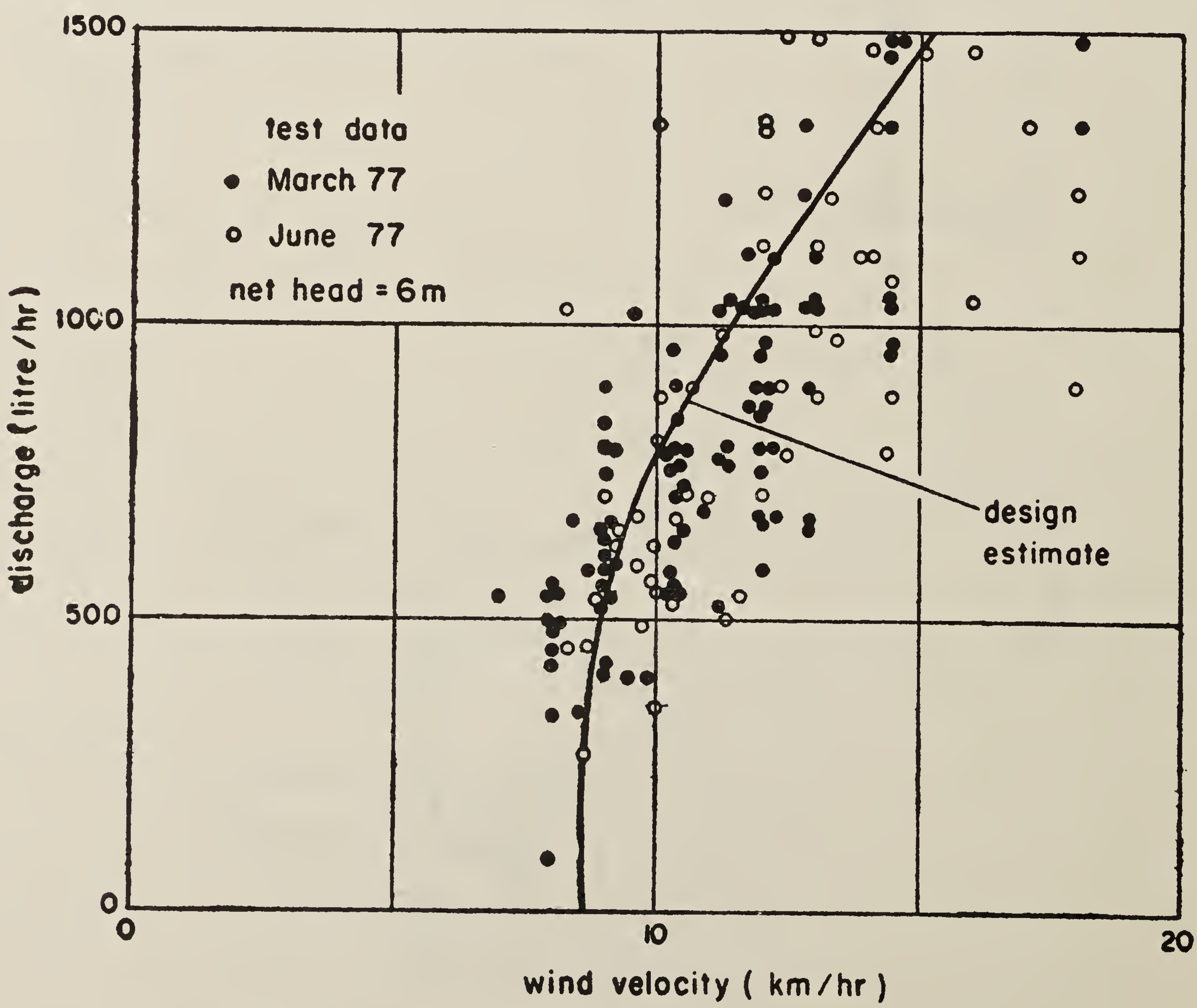

Figure 8. Performance of IISc windmill (prototype 1).

measured for one value of pump stroke and head of water. There is some scatter in the measurements because it was not possible to obtain perfectly steady conditions during the tests. However, the agreement between the estimates and measurements is seen to be satisfactory, indicating that design estimates can be relied on for any other stroke and head of water.

It can be noted here that, for the conditions represented in figure 8, the best efficiency of the system is about 12% at a windspeed of 10 km/hr. As indicated earlier, this efficiency is sustained only over a narrow windspeed range and there is a rapid fall-off with increase of windspeed. For example, the efficiency at 16 km/hr is only 6% and consequently the net pumping power is only 25 W. By an increase of pump displacement, the same system can deliver a net power of up to 40 W at 16 km/hr; but this will lead to a higher starting speed and reduced utilisation of lower winds. Thus, an optimal variation of pump displacement with windspeed over a range can result in a substantial increase of net energy output besides improving starting performance. Manual setting of crank arm to achieve this is not fully satisfactory because of the frequent attention such a scheme calls for. At present, an automatic variable arm crank to effectively do this, at a first cost of only a few hundred rupees, is being designed, and this device when installed is expected to yield a substantial increase in the output of the windmill-pump combination.

9. Field experience

The second prototype, constructed at the village Ungra (about 100 km from Bangalore), has been in operation since September 1977. The system has been delivering an average of around 2500 litres of water a day since that date. The problems of maintenance have been minimal. Apart from lubricating the rubbing parts, bolts and nuts had to be checked and adjusted occasionally for tightness because the timber frame has undergone some shrinkage. The rotor had to be lifted up (by using packing pieces at the supports) by a total of about 5 cm to take up the sagging of the support beams during the above period. The safety wire successfully operated thrice during this period and was reinstalled after every operation. During each operation of the safety wire, the windspeed exceeded 40 km/hr and the rotor was running on load. However, over the year, the sails of the windmill have been damaged. The damage is primarily due to the tears sustained by the sails when the safety wires snapped during development and during regular field trials. Recently, new sails, including rip stoppers and a slightly modified sail support system, have been installed.

Now some remarks about the durability of the windmill are in order. The largely metallic parts of the windmill including the mainshaft, the transmission and the pump appear to be in perfect condition after about one year of operation, and there should be little difficulty in their operating for several years more. The parts which employ solid wood—including the tower, which is unprotected, and the structural parts of the endplates, which are protected by a coat of coal tar—have shown little degradation, and a life of many years may be expected from them. The extensions to the end plates, which are of a weather-resistant type of plywood coated with coal tar, appear to be quite sound and a life of at least three years may be expected of them. Also, it may be possible to replace them later by inexpensive woven bamboo

matting. The sails of jute canvas, as mentioned already, had to be replaced within the year because of too many tears. With the improvements already incorporated, a sail life of upto two years may be achievable. The possibilities of using other materials for the sails to get a longer life are being considered.

10. Costs

The prototype windmills considered above were designed and constructed to establish the feasibility of building a windmill based on the novel sail-type Savonius rotor and using a comparatively low technology. Though costs have been held quite low, it is expected that they can be reduced further by careful redesign of components and optimisation of the geometry of the windmill. However, as an indication of the present state of development, table 1 gives a rough break-down of the costs incurred on the second prototype, which is shown in figure 1.

It may be noted here that the cost of a windmill of this type could be substantially lower than indicated here if built by the villagers themselves because they can procure timber more cheaply; and labour cost need not be accounted at the market rate if it is obtained on a mutual help basis. Many villagers who have seen the windmill have felt that the system would cost them only Rs. 2000.

11. Conclusions

It has been shown how a soft design, largely using materials and skills available in most Indian rural areas, could extract a reasonable amount of power from the wind for water pumping, at a first cost substantially lower than that of other designs with a comparable rating. Based on experience todate, it is felt that achieving a satisfactory life and scaling to larger sizes will not pose serious problems. Thus, this design appears to merit further study for use in a rural setting.

Table 1. Cost break-down of windmill and pump installation.

Item	Cost (in rupees)		
	Material	Labour	Total
Tower, including erection	350	250	600
Foundation	130	70	200
Rotor end plates, including painting	390	160	550
Sails with painting	120	80	200
Shaft, bearings, sail support wires and fittings	260	220	480
Pump	260	120	380
Transmission	190	90	280
Plumbing	150	—	150
Installation of rotor, transmission, pump and plumbing	—	150	150
Total	1850	1140	2990

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Plate 1

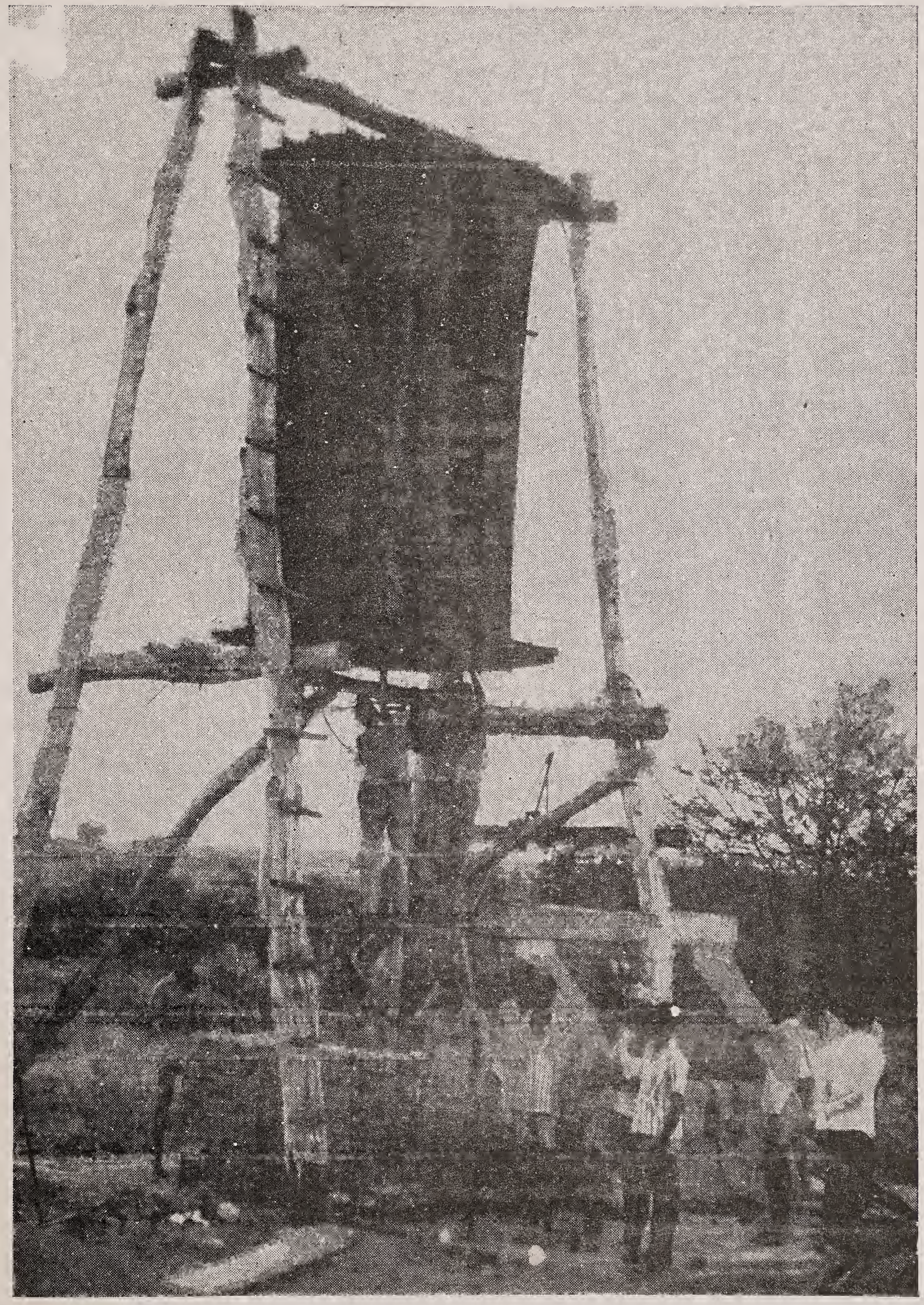

Figure 1. The windmill of the Indian Institute of Science (prototype 2), as set up at Ungra (Karnataka State).

Plate 2

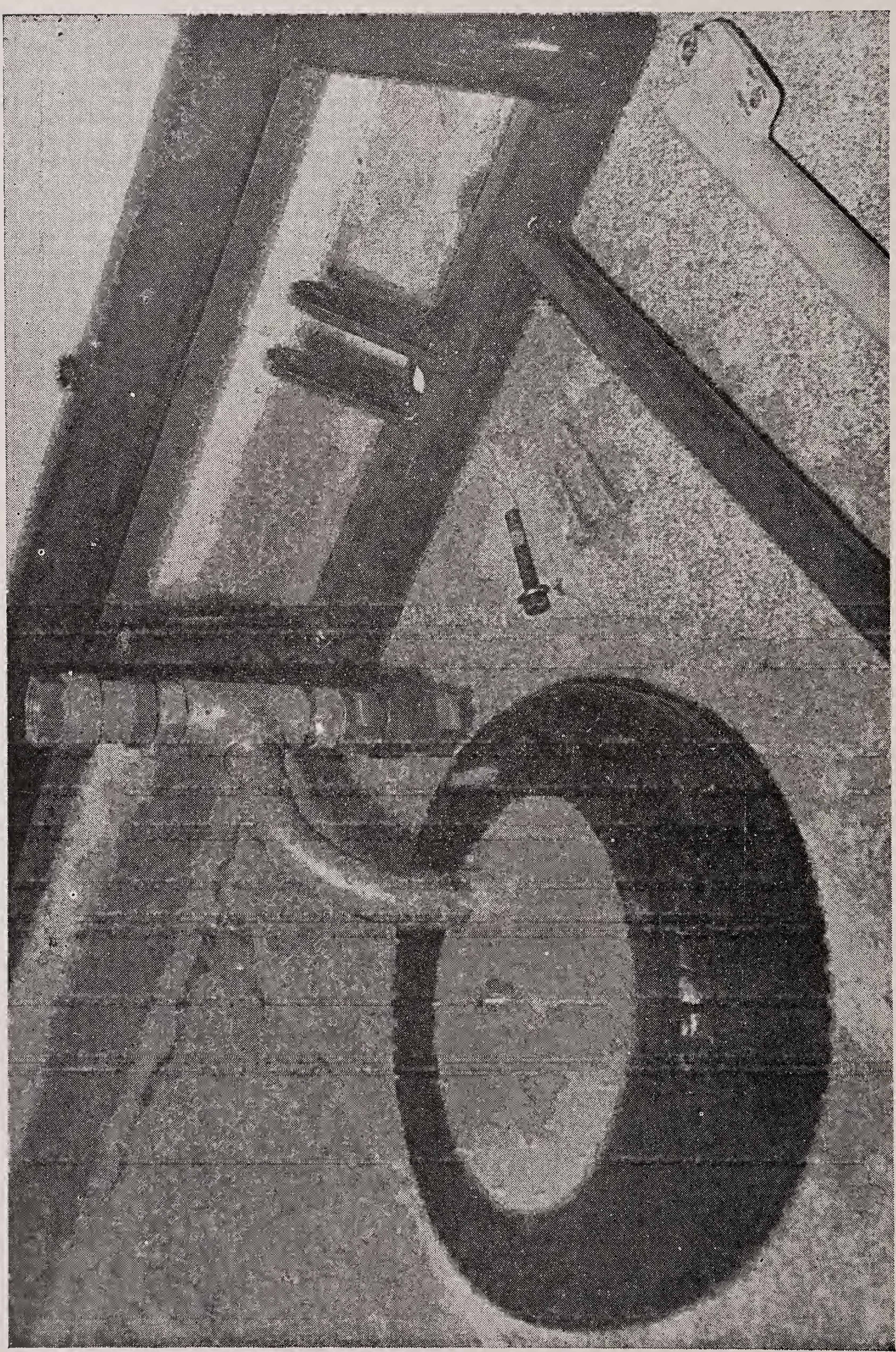

Figure 5. The tyre-pump.

The ITDG international windpump programme; engineering design considerations used in developing a windpump system for small-scale manufacture and use in under-developed arid or semi-arid regions

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Abstract. In this paper, some of the reasons why windpumps have not readily found widespread application in the less developed arid regions, despite the fact that they have been widely and successfully applied in the United States and Australia are discussed, in the context of the London-vased *Intermediate Technology Development Group*'s (ITDG) investigative work and field experience with windpumps.

Following from this is a description of ITDG's International Windpumps Development Programme which is intended to overcome some of the previous shortcomings of windpumps when applied in under-developed regions. Lastly there is an account in some detail of the engineering approach chosen in designing the ITDG windpump prototype for development under the International Programme which sets out to show how we feel we have identified a number of methods for either reducing the cost or increasing the output of machines of this kind.

Keywords. Windpumps; application in less developed regions; design; reciprocating pumps; horizontal-axis wind rotor; intermediate technology.

1. Introduction

The Intermediate Technology Development Group Limited (or ITDG), is a London-based, non-profit, research and development organisation committed to the promotion of technologies aimed at the needs of the poorer sections of humanity. The Group was founded by the late Dr E F Schumacher and colleagues, and practices the philosophy he popularised in such writings as the best-selling book *Small is beautiful.* In other words, we are primarily concerned with small-scale non-violent technologies that are economically and technically appropriate for people in the predominantly rural under-developed areas; simple criteria for judging what is ' appropriate ' is to see whether or not it will enhance the standard of living and the level of self-sufficiency of the users. Permanent improvements depend on the local people accepting the technology, so our Group is very concerned with end-use and end-users and therefore must seek to introduce innovations which will, at least ultimately, be manageable entirely by the people they are designed to help.

To this end, a primary concern has been the identification of small-scale power sources that are useful for performing commonly required rural tasks; one such task that seems particularly important is water pumping for irrigation of crops, for human

A list of symbols appears at the end of the paper.

consumption and for livestock, particularly as so many of the currently under-developed areas are arid or semi-arid. Conventional technology leaves little choice between the rope and bucket on the one hand, powered by human muscles and mass-produced petroleum-fuelled engines on the other for the half of humanity that lives beyond the reach of mains electrification systems. Mechanisation therefore demands an enormous jump economically and technically and the main beneficiary will inevitably be the industrial sector which at present has a virtual monopoly over industrial manufacture due to the large scale on which most products are generally manufactured. As a result, widespread investment in mass-produced machinery for the under-developed regions generally tends to widen the economic gulf between rich and poor both within and between countries, since most of the investment will go back to industrial producers, and their marketing and spare-parts infrastructure.

Nor does rural electrification seem to be a valid method for subsidising the rural areas in areas where the population distribution is diffuse and the people are poor since the economies of scale at the power station become unimportant compared with the high cost of building and maintaining the distribution network and the fuel requirements to overcome resistive losses. Even in India, with one of the most advanced and long-term rural electrification programmes, it has been shown (Makhijani 1976) that only 10% of the electricity produced goes to the rural areas where 80% of the people live. The same source claims that in Latin America only 2% of centralised electricity production is used in rural areas. Increasing future primary fuel prices will introduce greater diseconomies in centralised electricity production for rural areas, as the resistive losses will be worth more and the capital costs of new lines will reflect greater manufacturing expenses.

As a result, many people have pointed out the potential value of small-scale, decentralised power sources (Makhijani 1976; Anon 1976; Fraenkel 1976a; Mubayi & Tien Le 1977). Probably only the People's Republic of China is an example of a country where small scale, decentralised power has been systematically introduced, with 60,000 small hydroelectric stations, averaging only 36 kW each, completed by 1975 according to Smil (1976), plus a comparably large programme to introduce biogas production from animal and human wastes, and there is little doubt that these new energy resources must have played a part in improving the productivity and the standard of living of the Chinese rural population.

In order to try and make a contribution to the search for appropriate small power sources for use in rural development, our Group has a Power Project (among numerous other activities) which, in addition to investigating and publicising existing equipment that might usefully be applied, is also developing a number of new systems where it is felt there is a gap to be filled, virtually all of which make use of the so-called renewable energy resources of sun, wind and moving water.

This paper is about our windpump development programme, but before describing it in any detail, having already given some general background information about our Group, it seems worth mentioning some of the developments that led to our current programme on wind-energy utilisation.

Wind energy has for long appeared to us to be a particularly useful power source, since historically it was usefully applied when human technical skills were much less advanced than at present. Today it is still used on a much larger scale than most people realise in countries like Australia for water pumping and the wind is sufficiently ubiquitous to allow it to be used in a very much wider choice of locations than it is at

present. Before embarking on our programme, we studied a lot of data on the potential for using windmills in a variety of regions; important resources for this proved to be such references as Pedder (1938), Golding (1962), Parkes (1974), Munoz (1974) and Merriam (1972). Wilson (1975) is particularly interesting for us as he visited the Sudan in order to find out why a large number of imported windmills were no longer functioning; it is clear that although the familiar multi-bladed American farm windpump was probably a more important piece of technology than the six-gun in opening up the American Great Plains to cattle ranching and although some sources (Comet Catalogue No. 9 for example) estimate half a million wind-pumps still in use in Australia, the same machines have not been very successful in less developed countries.

In the early 1970s there was a popular view among development technologists that a solution might be arrived at by building ultra-cheap windpumps from industrial garbage; Savonius rotor vertical axis windmills built from the halves of an oil barrel, or windmills using old car differentials and crankshafts for transmissions. In fact a colleague of this author built two oil-drum Savonius rotors, one in Wales and one in Zambia. This approach seems fine in the hands of a skilled and enthusiastic field worker who is only seeking to build one or two windmills, but it becomes impracticable if a useful number of units are to be built and local people are to be trained to build them. Also, designs of this kind, although ingenious, do not have the productivity in terms of pumped water; nor are they sufficiently reliable compared with imported factory-built machines, which themselves have been shown to have shortcomings in the poorer rural areas. Lastly, there seems an unfortunate irony in trying to use industrial jetsam to solve the problems of people who have been missed by the industrial revolution, which makes jerry-built machinery of this kind a psychologically unattractive solution.

Therefore we were most interested in an opportunity which arose duiing 1975 to participate in a most unusual experiment then taking place in southern Ethiopia, to introduce a version of a sail windmill developed on the island of Crete, so that semi-nomadic Ethiopian villagers in a remote area could irrigate their crops. These windmills had to be made from imported materials as the region, being semi-desert, had no indigenous materials. Steel angles and pipes were readily available in Addis Ababa and were chosen as being longer-lasting than timber; the chosen design could be built with little more than a drill, hack-saw and welding set. During this author's visit in 1975, some 20 windpumps were in regular use by local people for simple flood irrigation which enabled them to produce a host of crops they had never been able to grow before, including a variety of fruits; and they were also growing their traditional crops to obtain three harvests per year instead of one. Naturally these machines (figure 1, plate 1) were of great interest in the region, as famine for half the year was an almost normal state of affairs. Since then 40 further windpumps have come into use.

In this project, we came across a serious attempt, not just to demonstrate a working prototype, but to perfect a design and then produce a sizable quantity of units which would function as reliably as possible. The author of this paper has detailed this project (Fraenkel 1976b) and shown that useful though machines of this kind are, they have to be heavily subsidised to allow their use by subsistence farmers (which may of course be a good use for rural development aid money in some situations). It was clear from this work that although the windmills could be quite simple mechanically,

they required reasonable structural integrity to function reliably and to withstand the substantial occasional transient loads caused by gusts, people climbing up the towers, pump-rod shocks caused by water hammer, and the like. Excessive zeal in paring down the dimensions of components in order to save costs had to be countered by the need to prevent stress levels that would result in premature fatigue of mechanical parts.

In the end it becomes clear that a good windmill, in common with other successful devices using supposedly free energy sources, depends on finding the correct compromises between achieving good system efficiency and reliability without making the system unacceptably expensive. In many situations the author believes windmills may have to be more expensive than seems acceptable to achieve minimum technical requirements, and then they can only be applied if subsidised. It is pointless wasting money on a ' cheap windmill ' which does not function adequately.

Our experiences in Ethiopia pointed to a number of innovations that might make small water-pumping windmills more effective; for example we were able to demonstrate very significant improvements in water output to be gained simply by using a double-acting pump. The work also indicated to us that there is a practical lower limit in cost below which it is no longer realistic to build a satisfactory and useful windmill; depending on local conditions and expressed in the loosest possible sense as an order of magnitude rather than a firm rule, this cost level is likely to be between £100 and £200 Sterling (US $200 to 400). This is because even the smallest windmill needs to be mounted on a tower and includes a minimum quantity of structural components and the lowest acceptable strength level must allow for transportation, erection and stresses of people climbing on it.

Since this cost level probably puts windmills beyond the reach of the individual small subsistence farmer (although it is within the reach of the already moderately successful producer of cash crops), both our groups and the American missionaries experimenting in Ethiopia began considering communal windmills shared between a number of small farmers, since what the farmer needs is not windmills but water, which is a readily sharable commodity. If larger and more expensive windmills can be considered, then considerable economies of scale can be obtained and water can be pumped at a lower unit cost. Experience with the Ethiopian windmills also pointed to the need for sufficient design sophistication to minimise the need for maintenance and repairs in the field; it is far easier to spend a little extra in man-hours and materials at the construction stage than to send skilled people on time-consuming trips at frequent intervals to make minor repairs. As a result the specification of the windmill currently under development (see figure 2) began to take shape.

2. Objectives of the windpump development programme

Despite the fact that windpumps have been successfully used in very large numbers in Australia and the United States for a century and that recent increases in the price of petroleum-based fuels have encouraged something of a revival of their popularity in competition with engine-powered pumps in those countries, they have not been applied on any scale or with much success in less-developed countries. This is despite the fact that economic and technical assessments have indicated that they would serve a valuable purpose in developing the all-important farming sector and would

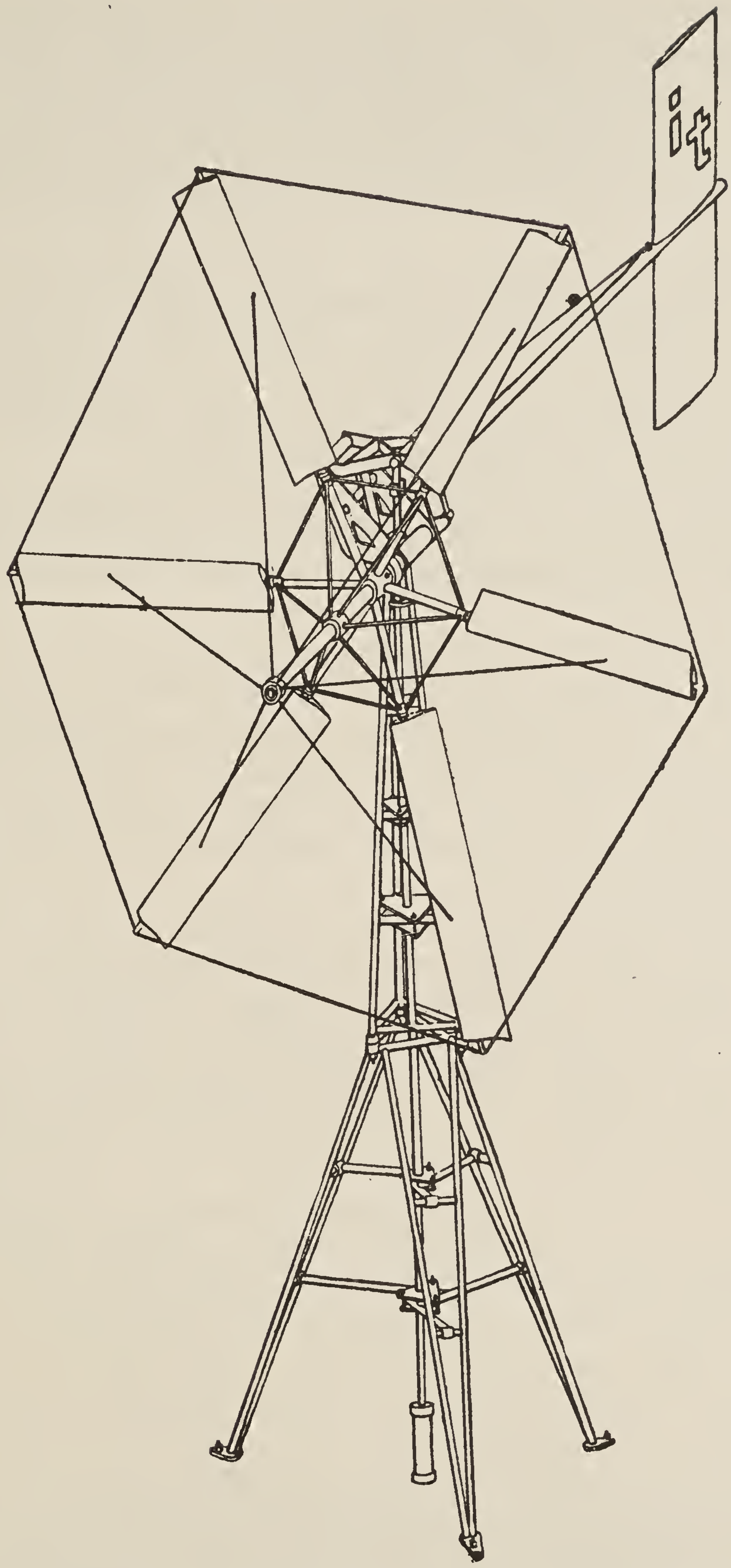

Figure 2. General view of ITDG UK prototype wind-pump shown with high-speed rotor

require less foreign exchange than is generally involved in using diesel pumping sets, which have been more generally favoured in such areas (see, for example, Parkes 1974).

Recognising this, various countries have considered importing Australian or American farm windmills, mainly to save petroleum fuel imports in the wake of the 1973-74

OPEC price increases, but all such efforts have been on a small scale and rather unsuccessful. India even looked at this problem as long ago as 1961 (see Nilakantan *et al*); a US \$1·4 million proposal to import windmills into Ethiopia was mooted in 1976 (Ethiopean Water Resources Authority), and so on. We think we have identified a number of reasons why such schemes to import traditional windpump designs proved non-starters.

(i) Windmills have a relatively high capital cost when imported compared with diesel pumps of the same capacity, although owing to their longer lives and low running costs they are almost always eventually cheaper. However, shortage of foreign exchange makes the lower capital investment for diesel plants generally more attractive in the short term.

(ii) The relatively great bulk of a windmill increases its shipping costs compared to engine driven pumps, particularly where transport distances are great. An Australian windpump landed in Africa is commonly twice the factory-gate price.

(iii) Small existing sales for imported windmills create a vicious circle because agents and distributors are inhibited from creating an adequate spare-parts and repair service to cater for rather few windmills, while the small number of sales encourages them to seek a greater margin in pricing than would apply to faster-selling, shorter-life equipment (like diesel pumps!). Also, there is a lack of experience and expertise at specifying the correct wind-pump sizes to satisfy local conditions.

(iv) Existing American and Australian farm windmills were mostly designed many decades ago, with the result that by current standards they are excessively material-intensive and expensive to build. Existing manufacturers are unlikely to incur the expense of redesign and retooling to produce more cost-effective designs, since the disadvantages of their current models are only strongly marked as far as their presently very small export markets are concerned.

(v) Although licence manufacture of existing American or Australian windpumps may appear to be a possible solution to the problem of providing reliable windpumps in less-developed countries, investigation of existing designs shows that they require production processes demanding a relatively large manufacturing volume due to the large capital investment intrinsic in the tooling and treatment processes; many components are pressed, stamped, forged, cast or hot-dip galvanised. As a result, the only countries licence-manufacturing American or Australian windpumps are ones which already have well-developed and prosperous commercial farming industries such as Argentina and South Africa. It is also noticeable that windpump manufacture in those countries does not significantly benefit the poorer farmers who simply cannot afford them.

(vi) The problems are to some extent exacerbated by the fact that many of the countries that could benefit from windpumps lie in the tropical belt, with rather moderate winds compared with more temperate latitudes. As a result the most appropriate windmills for their needs, to yield respectable quantities of water, are rather large ones, which are of course the most expensive both in terms of f.o.b. costs and shipping costs.

Bearing these points in mind, our group at ITDG has attempted to define a windpump that might overcome some of these problems. We decided that ideally what is needed is a design which would perform with comparable productivity and reliability to the best of existing commercially manufactured equipment, but which would be both less material-intensive (i.e. lighter) and involve only production techniques that are already available throughout the world in small and medium-sized engineering and maintenance workshops. In other words, jigging, tooling and special processes were to be minimised and construction was to be from standard steel stock using no more than a certain amount of lathe and milling machine work, plus cutting and welding.

As no design of this kind appeared to be available, the Group decided during the course of 1975, to set up a project aimed at developing one. We produced a project proposal defining work aimed at developing a series of prototype water-pumping windmills suitable for low-volume production using conventional and widely available materials and facilities. The end use for the machine was to be mainly in non-industrialised countries, (or in the less-developed rural sector of industrialised countries), at village level, for irrigation purposes and communal water supply use. The machine was to be designed to offer the following advantages, in the hope that this will make it more acceptable and successful than previous attempts to use windpumps.

(i) Labour requirements for manufacture could be met from local sources, thereby creating a number of new jobs and ensuring that a large proportion of the investment in each windmill goes back into the local economy.

(ii) Spare parts, maintenance and repair facilities would be greatly facilitated by the presence of the manufacturing unit close to the place of use.

(iii) Foreign currency requirements would be greatly reduced since they would be restricted solely to non-indigenous construction materials.

(iv) Transport and middle-men costs would be very much more modest than for imported machines, and again, any such expenditure would be fed back into the local economy.

(v) Certain technical innovations promised the possibility of improved performance coupled with reduced maintenance requirements compared with existing commercially manufactured machines.

(vi) Further cost savings compared with conventional imported windmills could be obtained by reducing the relative material-intensity of the ITDG design.

3. Procedure

It was decided to embark immediately on the construction of a prototype to test out various technical ideas. This work was started in December 1975 at Reading University in the UK, and the first prototype, illustrated in figure 3 (plate 2) was completed in August 1976.

A much more rigorous testing and proving programme was required than would be possible under the conditions at Reading, both to prove the proposed design for ease and economy of manufacture and to test its performance and reliability in the field. Therefore an International Development Programme was proposed in which it was suggested that six further prototypes, based on the lessons learnt with the UK version, should be test-manufactured and field-evaluated in six different overseas locations.

The participating institutions which were to build the overseas prototypes were chosen so as to represent locations where windpumps could realistically be placed into economic small-scale manufacture on the completion of the development and testing programme. To encourage a feeling of commitment to the programme, ITDG defined the project proposal to allow for the Group to provide external funding and consultancy services to support the overseas participants, but we asked that they should make a major commitment of their staff and construction resources. This proposal was in the event fully funded by the UK charity *Christian Aid*, who are currently concerned with trying to seek outlets for aid moneys which will lead to permanent reforms in deprived areas, rather than temporary palliatives.

At the time of writing, the project has grown slightly larger than originally envisaged due to the considerable amount of interest that became apparent once we publicised it. Prototype windmills are shortly to be built and tested in Botswana (two prototypes), Zambia, Kenya, Egypt, Oman, Sri Lanka, Antigua and possibly one other, yet to be finalised, location. Some of these projects are wholly self-financing as our budget was inadequate to include them.

Having completed the prototype in the UK and started testing it, and having identified our various overseas collaborators, we prepared a detailed design package consisting of a set of drawings illustrating a modified version of the original prototype in full detail to allow the overseas participants to build their versions. The design philosophy has been to err on the side of design sophistication to ensure that prototypes of reasonable quality can be built; they may be more expensive than seems attractive for a production model, but it seems better to start with something technically more-than-adequate and improve its economics by value engineering later, rather than to risk putting the concept into disrepute by risking cost-saving elements that may excessively degrade the design at too early a stage. The principles applied in this design in any case lend themselves to a host of variations which may offer either performance increases or economies in construction and it is hoped that the multiplier effect of involving a lot of fresh minds in the project from the overseas collaborators will result in a wide variety of suggestions for improving the system as the programme progresses.

4. Technical description of the design concept

It was decided at an early stage to use a conventional horizontal-axis windmill configuration rather than one of the novel vertical-axis arrangements currently being investigated in various places, since this would guarantee us reasonably predictable performance coupled with easily arrangeable storm protection. Since a horizontal-axis windmill needs to be faced into wind to work, it can equally be turned out of wind to stop it or to protect it from storm damage. This is more important than some people may immediately appreciate, as the energy in the wind is proportional to the cube of the wind speed—in other words there is a thousand-fold increase in energy flux between a windspeed of 5 km/hr and 50 km/hr. As our windmill would need to function down to windspeeds as low as 5 km/hr in some situations and to inevitably withstand occasional storms of 100 km/hr and more, the provision of automatic protection from storm damage seemed a fundamental one.

We also decided at an early stage, partly on the basis of experience gained with the Cretan windmills mentioned earlier, that considerable gains could be had in system efficiency by working on the pump rather than the rotor design. For example, a double-acting pump offered clear advantages over single-acting ones, which seems curious when it is borne in mind that virtually all factory-manufactured windmills use single-acting pumps.

In fact, the main reason for the use of a high-solidity multi-bladed rotor on conventional farm windmills (see figure 4, plate 3) is to achieve the high starting torque needed to move a deep borehole pump from rest when using the diffuse energy flux available in windspeeds of the order of 5 to 10 km/hr. Once the motion has commenced, the inertia of the windwheel overcomes the torque peaks demanded by the pump and the large number of blades become aerodynamically counter-productive as high-solidity wheels can be shown to have considerably reduced conversion efficiency. Figure 5 illustrates how variation in rotor solidity (defined as $\sigma = Nc/2\pi R$ or the proportion of metal effectively filling the rotor circumference) affects the coefficient of performance of the rotor C_p and the optimum tip-speed ratio $\lambda(=\Omega R/V$, which is the speed ratio of the rotor tips to the free wind stream). In general, extra blades not only interfere with the efficient performance of the rotor (except ironically in theory it can be shown that at higher tip-speed ratios extra blades at a given solidity will reduce tip losses, although in practice it is difficult to engineer a lot of slender blades—references such as Jansen & Smulders (1977) give a good broad introduction to windmill rotor theory), but extra blades also cost more. Since the economics of the windmill depend on intercepting the maximum possible cross-section of air-stream with the minimum possible weight of materials in order to keep costs down, there is some attraction in looking at the possibility of using lower solidity rotors where possible.

Further advantages accrue if a lower solidity rotor can be used. For example, with only a few blades the marginal costs in increasing the blade radius are reduced and it can be cheaper to consider putting a larger rotor on a shorter tower than to follow conventional practices of raising the rotor on a high tower to take advantage of slightly higher windspeeds resulting from the velocity gradient inherent in windshear near the ground. References such as Dörner (1975 and 1977) and Hütter (1977) point to the superiority of low-solidity horizontal-axis wind energy converters (WECs) in terms of area of wind-stream intercepted per unit weight of structure. However, figure 6 illustrates that the torque produced by a low-solidity rotor,

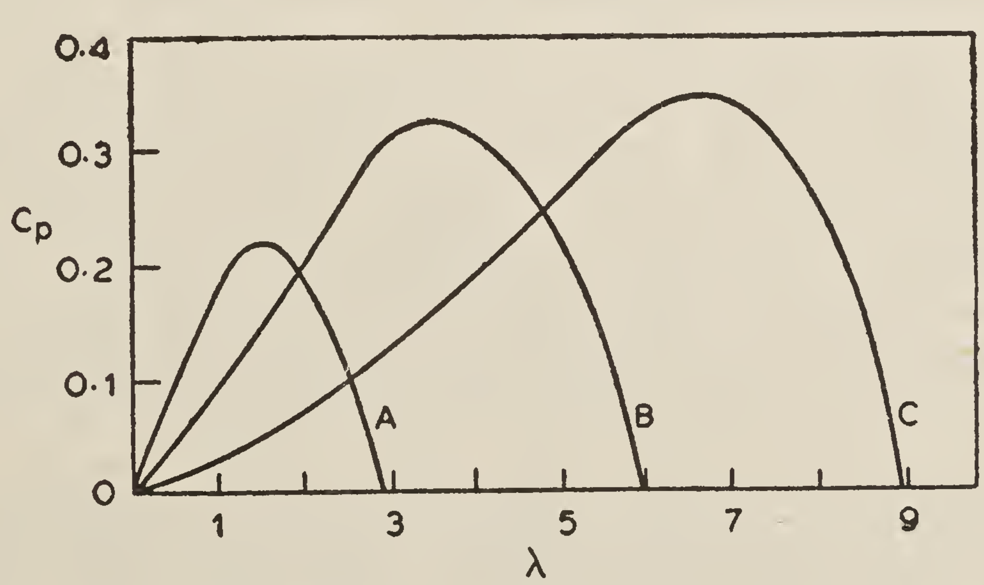

Figure 5. Curves illustrating the variation of performance coefficient with respect to tip-speed ratio for three windmill rotors of high, medium and low solidity respectively.

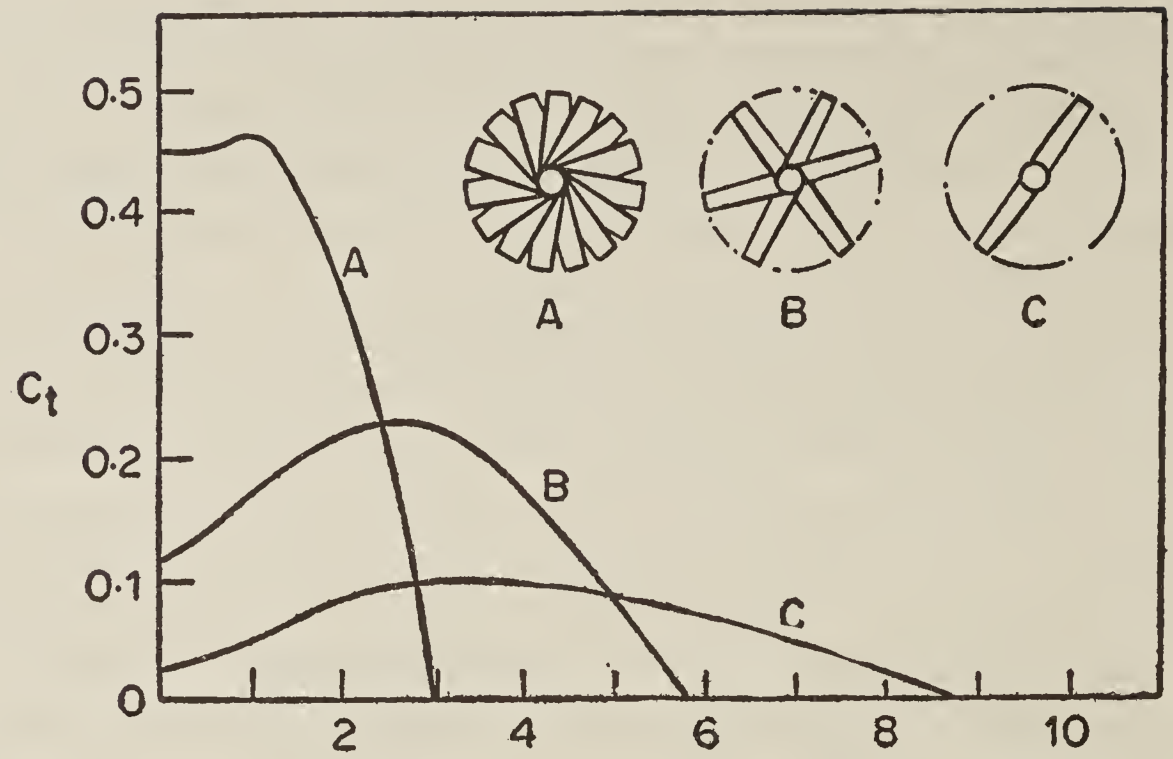

Figure 6. Same as figure 5, but showing the variation of torque coefficient.

particularly for starting, is very much reduced compared with a conventional multi-blade rotor. Also, there are problems in driving reciprocating water pumps at speeds in excess of around 60 strokes per minute. So a high-speed rotor water-pumping windmill may in theory be more efficient and less material-intensive, but it also introduces very real pump-matching problems.

We decided to search for a compromise solution. A high-speed low solidity rotor for low lift applications, where a double-acting high-speed reciprocating pump could be applied with air-chambers and other innovations aimed at minimising problems caused by driving it at speeds of up to 200 strokes per minute, and a more conventional high-solidity, slow-speed rotor for driving conventional deep bore-hole pumps and to provide a ' fall-back ' if problems with the more innovative high speed rotor proved it to be impracticable. This seems justifiable as high efficiency is only important where high flows of water are needed, such as for irrigation, which would normally only be attempted in low head locations. Torque seems more important in deep pumping situations, where reasonably frequent but more modest water outputs are likely to be needed. We did of course consider using a high speed windmill with a gearbox to drive deep-well pumps and we also looked at high-speed windmills with centrifugal pumps for low lift applications; however, gearing and gearboxes were felt to be too complex for easy small-scale local manufacture and without gearing (up) even a high speed rotor was not fast enough for a centrifugal pump unless unacceptably large pump runners were used, or very low lifts were required.

Evaluation of various rotors revealed some interesting points about traditional multi-bladers. Firstly, they operated at such low Reynolds Numbers (Re) that thin cambered metal plates actually have the advantage in that kind of flow regime over an aerofoil, but we found that if we moved from a tip-speed ratio of say 1·75 as is conventionally used for farm windmills, to one of around 4, going in the process from around a couple of dozen cambered-plate blades to six blades, we were operating at Reynolds numbers in the 10^5 plus range where aerofoils become advantageous. Structurally we could also consider cantilevered blades in order to eliminate the complex system of rings and spokes needed to support the many blades in a farm-windmill rotor, as the aerofoil would effectively act as a faring for a cantilever spar which would otherwise cause a lot of drag.

In the end we decided to try and design a standard tower, transmission, tail and governing system and to offer two alternative rotor and pump combinations to suit low-lift-high-volume and high-lift-low-volume pumping needs, since indications were that high speed rotor problems were soluble.

Other primary conceptual decisions were to use conventional governing systems for storm protection—i.e. to mount the rotor off-centre from the tower axis so that the wind would try and rotate the rotor in a vertical plane to the rear of the tower but by providing a hinged tail vane, held by a spring at ninety degrees to the plane of rotation; the rotor is held perpendicular to the wind so long as the wind loadings on the rotor are insufficient to overcome the pretension in the tail boom spring; once the spring preload is overcome the rotor begins to jack-knife towards the tail until in a full storm position it is completely edge on to the wind. By varying the geometry of the tail boom hinge and spring fixings, it is possible to make the folding process progressive or sudden and to introduce an element of hysteresis to prevent undue hunting of the rotor when the wind is close to the governing threshold. Adjusting the spring tension allows the windspeed at which governing takes place to be varied and the system is fail-safe in the sense that if the spring or one of its connections broke or came disconnected in some way, the windmill would simply fold as in a storm and become inoperative but safe from damage until the spring tension was restored. It is also possible to provide a ready means for deactivating the windmill by winching the tail into the furled position by winding in on a linkage connected to a winch at ground level; this linkage is connected through the pump-rod housing to allow the motion to be transmitted without interfering with the orientation of the windmill when it responds to changes in wind direction.

The final major conceptual decision, hinted at earlier when the objections to gearing were mentioned, was the choice of a simple and novel transmission for converting rotary to reciprocating motion. Here it was important to keep the main rotor shaft axis as low as possible relative to the tower-head thrust bearing to minimise the toppling moment of the head mechanism, which dictated that, in common with most factory-manufactured windmills, the connecting rod should operate with its reciprocating end above the crank rather than below it. However, most windmills use a system with a sliding cross-head to locate the reciprocating end, which poses a major lubrication problem unless the entire mechanism is enclosed and oil lubricated, which is the conventional solution. Our transmission (figure 7) avoids this problem by using a radius arm or rocker arm to locate the upper connecting rod end and which also carried the pump rod train; this rocker can conveniently be pivoted on massive semi-rotary bearings which are lightly loaded and easily lubricated. As a result we have attempted to avoid oil lubrication and opened up the possibility of introducing modern dry bearings needing no maintenance at all; in addition, avoidance of the need for a sump and oil containment, plus large numbers of seals, has greatly simplified the transmission and resulted in very substantial weight (and cost) savings compared with comparably sized commercial products as will be detailed in the conclusion to this paper.

Before discussing some of the ' nuts and bolts ' of the design, it is well worth concluding this section on the basic concepts by outlining the conclusions of some important work, as yet unpublished, completed by a collaborator in the design work for the pump and governing system, Dr John Dixon. Dixon (1978) has analysed some typical wind regimes and produced some interesting conclusions, that support the

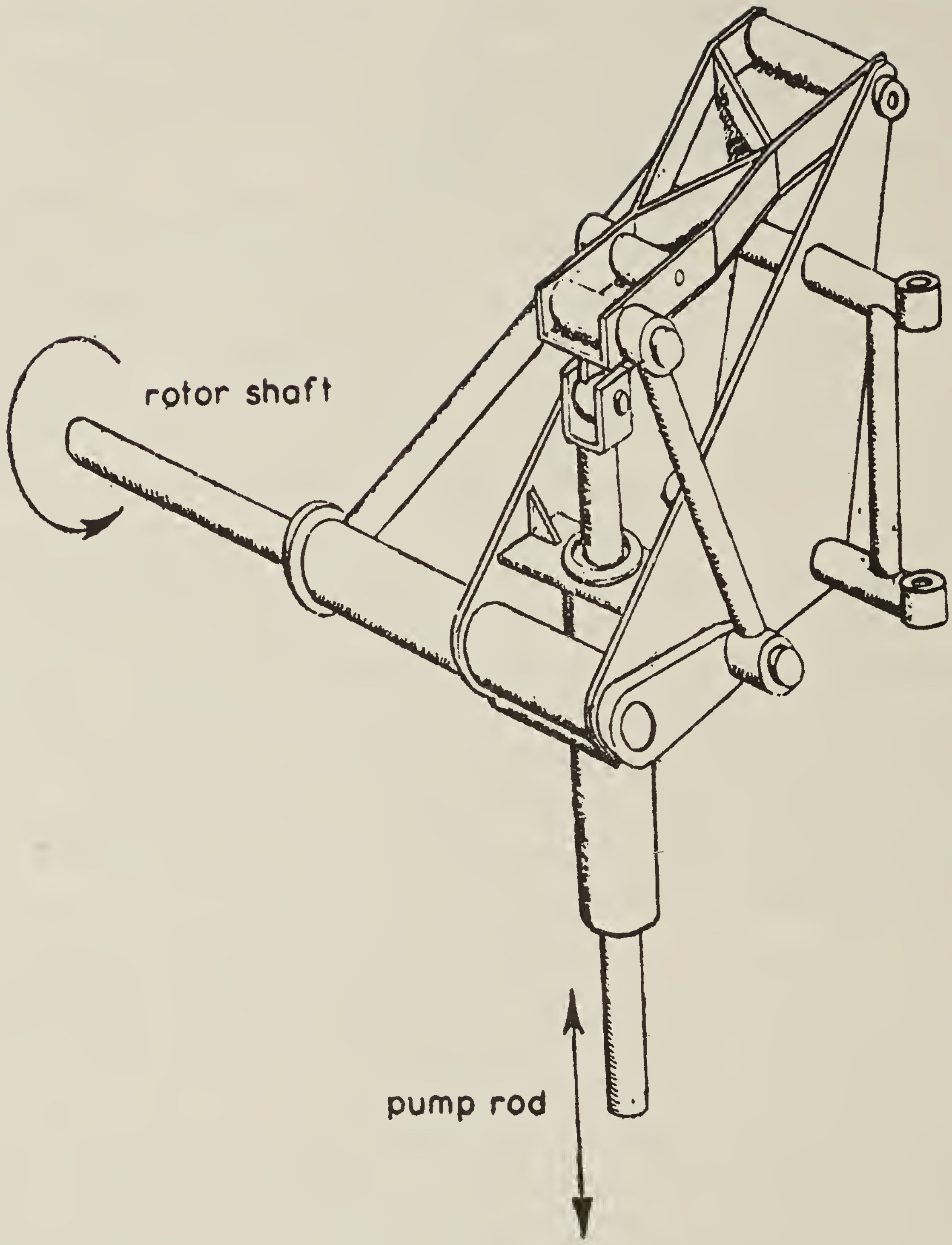

Figure 7. Schematic view of the ITDG windpump transmission system for converting rotary to reciprocating motion, which has allowed great reductions in windmill 'engine weight' compared with most commercially available machines which are invariably fitted with heavy oil containments.

conceptual thinking behind this system. In brief, he has shown a number of important effects inherent in wind energy conversion and in matching windmill rotors to reciprocating pumps, possessing cyclic torque characteristics:

(i) About 90% of the useful energy in a given wind regime lies in the wind spectrum from V_m to $3V_m$ (where V_m is the mean wind speed).

(ii) He has defined a parameter G called the torque ratio which is equal to T_p/T_m or peak torque requirement per cycle divided by mean torque requirement. Assuming sinusoidal motion, $G=\pi$ for a single-acting pump and $G=\frac{1}{2}\pi$ for a double acting pump (and $G=1$ for a constant torque pump). A windmill will start up once the torque produced exceeds T_p but once started will continue to run until the torque falls below T_m; in other words there is a wind speed range such that the windmill will only operate if it previously has experienced the windspeed required to produce T_p which is defined as V_s (start up wind speed). The higher the value of G, the broader the windspeed range between V_c, the minimum windspeed for continued operation, and V_s. Dixon has shown that there is a major matching problem,

too complex to detail here, which means that even if a pump and rotor are optimally matched, a single-acting combination can at best only have a matching efficiency of 16% a double-acting pump combination 27% and a constant torque device ($G=1$) 39%, where matching efficiency is defined as

$$\frac{\text{total energy into pumped water}}{\text{rotor energy output potential}}.$$

As a result, as is well known, although a conventional single-acting farm-windmill may have a system efficiency of the order of 30% at its optimum wind speed, due to the amount of time when the wind is not at the optimum the overall efficiency of conversion of the wind spectrum is unlikely to exceed 5%, as is borne out by manufacturers' published output figures.

Dixon's analysis has confirmed what practical experience coupled with previous less rigorous assumptions had indicated earlier, namely that a double-acting pump will quite simply result in a 60% improvement in overall utilisation of the wind-energy spectrum. Further modifications to the pump torque requirements, such as the introduction of controlled leakage to facilitate starting, offer the prospect of doubling the total output compared to a conventional single-acting pump; i.e. two windmills' output for little more than the price of one. Much of our work reflects this conclusion.

5. Details of the various sub-assemblies

The following paragraphs detail the methods chosen in an attempt to apply the requirements already described.

5.1. *Rotor configurations*

Initial work concentrated on the proposed high-speed low-solidity rotor since many more unknown factors were involved in applying this. The prototype version of this is illustrated in figure 2 and figure 3 (plate 2) and it consists of six parallel-chord, cambered aerofoils. Overall rotor diameter is 6 m (20 ft) and the thickness/chord ratio is approximately 9%. We did not attempt to reproduce any specific aerofoil section or to achieve the optimum plan profile, since providing we obtained a clean section we felt any gains in that quarter would be quite marginal and unimportant compared with the gross matching inadequacies already pointed to. However we did seek to obtain the optimum blade twist, not so much to obtain good aerodynamic efficiency when at speed, but in order to try and achieve a considerable improvement in starting torque compared with untwisted blades of the same tip-angle of pitch.

The blades were made by folding aluminium skin sheets lengthwise to form their leading edge and then wrapping them around a spar located at ⅓ chord and rivetting the trailing edges together by hand. The whole assembly was subsequently filled with a polyurethane foam mixture to give it more rigidity by tensioning the skin. The twist was obtained by a clever process devised by another colleague of mine, Dr John Armstrong, who did a considerable amount of the initial detail design work on the prototype; under this process the skin sheets were non-uniformly stretched so as

to strain the two edges permanently by pulling the ends beyond the yield stress for the edges, while leaving the centre line that forms the leading edge unstrained. As a result, the trailing edges were made marginally longer than the leading edge and automatically seek to take up a twist which, due to the thin and flexible nature of the sheets, can be quite easily adjusted to any desired angle prior to rivetting the trailing edges and fixing the twist. The prototype blades were made by stretching the sheets of metal with an overhead workshop crane, but we are working on a simpler method of either rolling the edges of the sheet to strain them or of using a simple rig based on a small hydraulic jack to pull the sheets into shape. Although this sounds complex, in fact the only equipment needed other than hand tools is ideally a sheet folding machine (although this is not essential), and either a crane or rollers or a jig incorporating a small hydraulic jack. The efficiency of the resulting rotor is considerably higher (of the order of 50%) than a typical multi-blade rotor at optimum tip-speed ratio, and, more important, it only weighs around 80 kg for the entire rotor, compared with a weight some 400–500% greater for a comparable diameter multi-blade rotor; this of course represents a considerable saving in materials and costs, although the

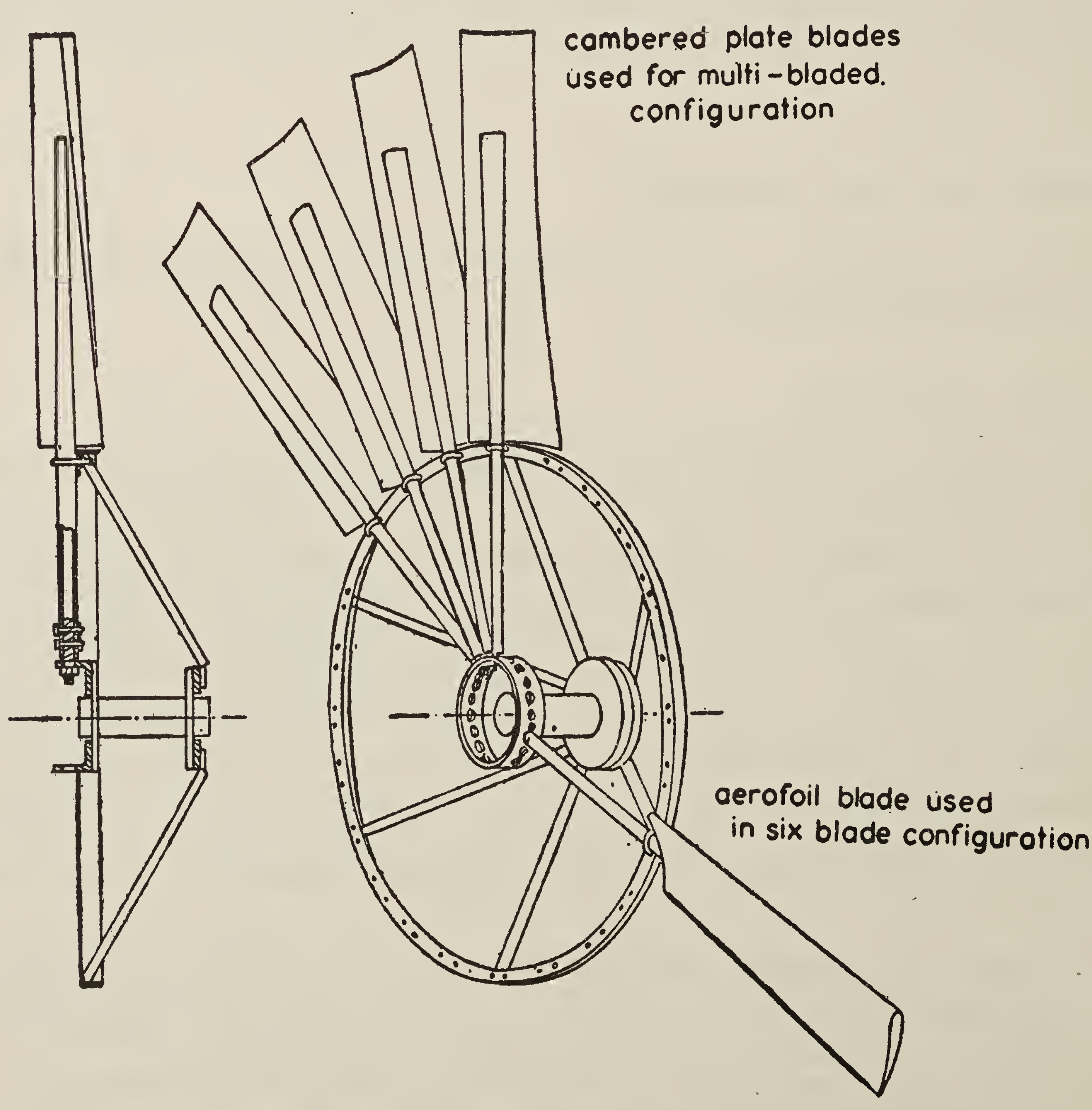

Figure 8. Multi-purpose rotor hub for the ITDG windmill, illustrating how it can carry either 24-sheet metal paddle blades for high-lift and low-speed applications or 6 aerofoil blades for low-lift and high-speed purposes.

price per unit weight may of course be somewhat higher due to the need to use aluminium for the blade skins.

We braced the prototype rotor with stainless steel rigging wires to increase the safety margins, but now feel sufficiently confident in the blade design to eliminate these in future versions simply by introducing a number of minor improvements in the spar design, notably by avoiding the forward coning that introduced centrifugal-force-induced bending moments at the roots; this was originally included purely to increase blade tip-clearance while keeping the drive shaft short.

Figure 8 indicates the current rotor design we are working on; this incorporates an all-purpose hub capable of carrying a variety of different numbers and types of blades. The main reason for this is to allow either high-speed or low speed rotors to be assembled with the maximum possible number of common components in the entire windmill system. High speed rotors will normally carry six aerofoil blades mounted to coincide with the bracing struts (since the loading per blade is substantially higher with a high speed rotor while for driving conventional bore-hole pumps it is possible to fit 24 paddle-blades consisting of aluminium or galvanised steel cambered plates bolted to tubular spars.

The multi-blade rotor operates at Reynolds Numbers such that there is thought to be no great drag penalty from the spars—however the spars are progressively flattened to taper them into an oval cross-section towards the blade tips, as indicated in figure 8. Experimental work (Buehring 1978 and Dekker 1977, for example) indicates that at low Re values, lift coefficients (C_L) in excess of 1 may be obtained and more important, C_D/C_L as low as 0·7. Hence, although we have yet to test the multi-blade rotor, we do not anticipate any very severe performance penalty resulting from its simple structure, but it should be relatively inexpensive to build. It is also readily modified to different diameters to suit different wind-regimes by simply clipping or extending the blade assemblies.

Lastly, the ‘all-purpose hub’ will, it is hoped, permit experimentation with other blade construction materials by allowing us readily to fit a variety of blades including wooden ones, metal frames covered with doped fabric (like early aircraft control surfaces), fibreglass, sailwings and so on.

5.2. *Transmission*

The standardised transmission is stressed to carry the maximum torque expected from the low-speed (high torque) rotor. Hence it has a good safety margin to cope with transient shocks caused, for example by water-hammer, that might be developed in the lower torque high speed system.

Sealed, oversize, ball bearings are used for the main shaft on the prototype, but bushes could equally be used on future machines at a possible cost saving. The connecting rod, radius arm and pump rod link bearings on the prototype are all a mass-produced, plastic-lined, wrapped bush type of bearing known as *Glacier* DX and in some cases DU. The former only requires marginal lubrication, while the latter is self-lubricating and can run completely dry without ill effect. DX consist of an acetal resin co-polymer bearing surface bonded to a porous bronze substrate, while DU is a PTFE (polytetrafluorothylene) and lead combination. Both have remarkably good wearing properties compared with traditional bearing materials and despite their formidable-sounding composition are very much less expensive

than ball or roller bearings and much more compact to install. It is felt that in most cases, as they are such a small percentage of the total cost of the machine and as they offer the possibility of virtually maintenance-free operation, it is justifiable to import them into the country of windmill manufacture. However, where it is desired to eliminate as much as possible of imported components, the design lends itself to the use of more traditional bearings such as bronze, white-metal or even hard-wood impregnated with oil.

The transmission chassis frame, radius arm, mainshaft housing and tower-pivot journal are all made up from ordinary stock mild-steel plate and tubing. The thrust bearing which carries the whole windmill head on the tower is nothing more than a ring of hard nylon, which has proved perfectly adequate in operation and costs a fraction of the price of a commercial thrust race of the kind used in most manufactured windmills at present.

5.3. *Tail and governing mechanism*

The tail fin is simply a sheet of 22 swg aluminium folded, pop-rivetted to a spar at 1/3 chord and then rivetted at its trailing edge. The assembly is slotted into a tubular tail boom and finally fiilled with polyurathene foam, just like the aerofoil rotor blades, to stiffen it up. It could equally well have been made from thin sheet steel, albeit at a small weight penalty. The entire tail assembly is about 3·5 m from its pivot behind the transmission to the fin spar position. A bracing wire was originally fitted to support the tail boom, but this was replaced with a tubular tie after the bracing wire had been found to whip under certain conditions.

The governing system functioned effectively at the first attempt, rather to our surprise since it was difficult to establish an exact theoretical model for its behaviour. We did, however, find that although the furling action in a strong gust was progressive and smooth, after the gust subsided unfurling tended to be excessively violent causing the tail boom to whip, so we cured this problem by adding a small damper. Since it is hard to fabricate a damper we chose to fit a steering damper from a Land-Rover cross-country vehicle as these are relatively widely available and have an equal damping effect in either direction of travel.

The UK prototype does not have a mechanism for furling from ground level, but the design-package being used by overseas participants transmits pull from a winch or lever at the base of the tower via a slider mechanism below the transmission (which prevents the head from twisting the pull-out cable when it changes its orientation to face different wind directions, or from winding the pull-out cable around the pump rod) and thence it passes through the transmission pivot journal and over two pulleys before being attached to the tail boom.

5.4. *Tower structure*

The UK prototype is mounted on a rather short 6 m (20 ft) tubular steel tower consisting of a top frame assembly mounted on three, ladder-like, legs. The design package for the overseas prototypes suggests a modified modular version of this tower built up in 3 m high sections. There are five modules in all, the minimum tower height being 6 m as on the UK machine, with up to four 3 m additions below

being possible to achieve a maximum tower height of up to 18 m (60 ft) to the rotor centre line.

Tubular steel construction is favoured, since it allows a better strength/weight ratio and, more important, it is easier to paint effectively and lets rain water run off better than angle-iron structures, which in the absence of hot-dip galvanising seems important to ensure protection from corrosion. We are also seeking to reduce the number of bolted fixings, as it has been shown that loosening nuts and bolts in traditional commercial windmill towers can be a continuous maintenance problem. Most of the bolted fixings incorporate captive (welded) nuts and high tensile allen head screws to simplify assembly and to reduce the risk of pilferage of nuts and bolts that has been known to occur occasionally with windmills in the field.

Another important feature is that the tower, which is three-legged, is mounted on hinged feet, so that it can be assembled together with the windmill at ground level and the pulled up into the vertical position using either the vehicle that transported it to its site or by using a winch. We regard this feature as an important safety point as it will reduce the need for working high above the ground and will also allow repairs to be carried out easily and more safely by lowering the entire machine to ground level. Surprisingly, the only commercial windmill we have found to have this seemingly useful feature is the French *Neyrpic* machine produced by Ateliers & Chantiers Navals de Chalon sur Saone.

5.5. *Pumping arrangements*

We have developed a double-acting piston pump for low-head, high-volume pumping, which consists of a pvc (polyvinylchloride) cylinder with steel chambers at each end each fitted with an inlet and outlet valve and a closed aluminium piston fitted with a pair of leather cup seals. We fitted air chambers close to the inlet and outlet ports, since the relatively high piston speeds demanded an effective isolator between the piston and the pipeline to prevent water-hammer. This pump has been undergoing extensive testing on an electrically-powered variable-speed test bed, which rapidly revealed a number of shortcomings that we have overcome with suitable modifications.

The prototype pump has a bore of 150 mm (6 in.) and a maximum stroke of 300 mm (12 in.) giving a swept volume of the order of 10·6 litre per rotor revolution (double that of a single-acting pump of the same torque load). This allows it to give particularly high outputs in light winds, while at low heads it is possible to create dynamic effects that greatly increase the volumetric efficiency of the pump making it in effect a type of induction pump with a better torque matching relationship to the wind-rotor than a purely positive displacement pump. Work is still in hand on testing and evaluating this pump at present and we have a number of other pump variations in mind for later testing, including reciprocating inertia pumps with substantially improved matching potential.

We are also experimenting with methods of unloading the rotor in light winds in an attempt to conserve its momentum and reduce the parameter G defined earlier. One method under test at present is a pump bypass with various types of throttling control to effect a very leaky pump at low speeds to allow the windmill to accelerate, with progressive closing of the artificial leak as speed builds up.

For deep well pumping, as already explained we feel poor matching is less of a disadvantage as consistent water supplies rather than large outputs are needed. Also, there are problems in installing a double-acting high speed pump down a deep well, particularly with pump-rod buckling on the down stroke. We feel there are some prospects for achieving improved matching with bore-hole pumps by introducing modifications at the well head rather that at the pump and have plans to investigate this as soon as the development work on the low-head pumps is complete.

6. Conclusion

Initial indications are that modified versions of the UK prototype of our wind-pump design will be able to be economically manufactured in a number of different countries. We have achieved considerable savings in construction material—for example the weight of the high-speed rotor (6-bladed), transmission and tail assembly on our UK prototype is approximately 180 kg, while a comparable Australian windpump of similar rotor diameter has an ‘engine weight’ (i.e. the same windmill components excluding the tower) of the order of 1500 kg. With our multi-bladed rotor the ITDG total ‘engine-weight’ increases to around 380 kg which still represents a substantial saving. The main reason for this weight saving is the use of a fabricated, non-enclosed transmission; the Australian windmill cited above as a typical traditional machine has a cast-iron transmission housing which carries no less than 27 litres (6 Imp. gallons) of lubricating oil; no doubt the cast-iron enclosure weighs more than the entire ITDG transmission even without the drive train installed. The use of modern bearing design approaches permits the elimination of the complex and expensive lubricating systems demanded to ensure reliable operation with traditional commercially-manufactured farm-windmills. Other savings have been introduced with the rotor design, by introducing cantilevered blades on tubular spars.

We hope that it will prove possible to manufacture our 6 m wind-pump design at a cost of around £1000 Sterling (US $2000), where prices of steel and aluminium correspond to those prevailing in UK. Costs will of course vary depending on local conditions, windpump configuration and tower size. This would then be competitive with the capital cost of small diesel engine pumps in absolute capital investment terms, but involves much smaller foreign currency components in the first cost and no foreign currency in the running costs. With increasing petroleum prices the advantages will increase. Hence it is hoped that the final product of our international development programme will prove an attractive and useful tool in both rural and agricultural development in areas lacking sufficient pumping equipment at present.

Mention should be made of various colleagues who have at various times made major inputs in the development of this project. These include Drs John Armstrong and John Dixon for their contributions to the design, Messrs David Sanders, Dennis Wilkinson and Max Ewens for making many parts of it, Mr Norman Joyce for his innovative ideas and efforts in developing the pump and test rig and Professor Peter

Dunn for arranging to allow us the hospitality of the Alternative Energy Research Centre at Reading University in his department. Much of the draughtsmanship in preparing the design package has been in the hands of initially Mr Charles Preston and later Mr David Howden, with further assistance from Mr Malcolm McLaughlin and Messrs Flexstern Designs Limited. In addition a host of helpful ideas from our overseas collaborators, who at the time of writing are just about to start construction work, and from the voluntary members of our Group's Wind Energy Panel should be acknowledged.

Vital contributions were made from the secretariat of ITDG which absorbed a considerable proportion of the arduous administrative burden inherent in an international cooperative venture. Lastly, the most important helpers of all, without whom the entire project would not have been possible, are *Christian Aid*, who funded the overseas phases of this project and also provided for the initial prototype construction work in the UK, and the *Baring Foundation*, who provided the wherewithal to expand the activities of the Reading-based R & D programme considerably in order to provide better support for the overseas phases of the project.

List of symbols

c	chord length of individual blades
C_D	drag coefficient
C_L	lift coefficient
C_p	performance or power coefficient
C_t	torque coefficient
G	Dixon's torque ratio T_p/T_m
N	number of rotor blades
R	rotor tip radius
Re	Reynolds Number
T_m	mean torque requirement to drive pump
T_p	peak torque requirement per cycle to drive pump
V	free-stream windspeed
V_c	minimum windspeed for sustained operation
V_m	mean windspeed for particular windmill site
V_s	starting windspeed required to produce T_p
λ	tip-speed ratio (defined in text)
σ	rotor solidity
Ω	angular velocity of rotor

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Plate 1

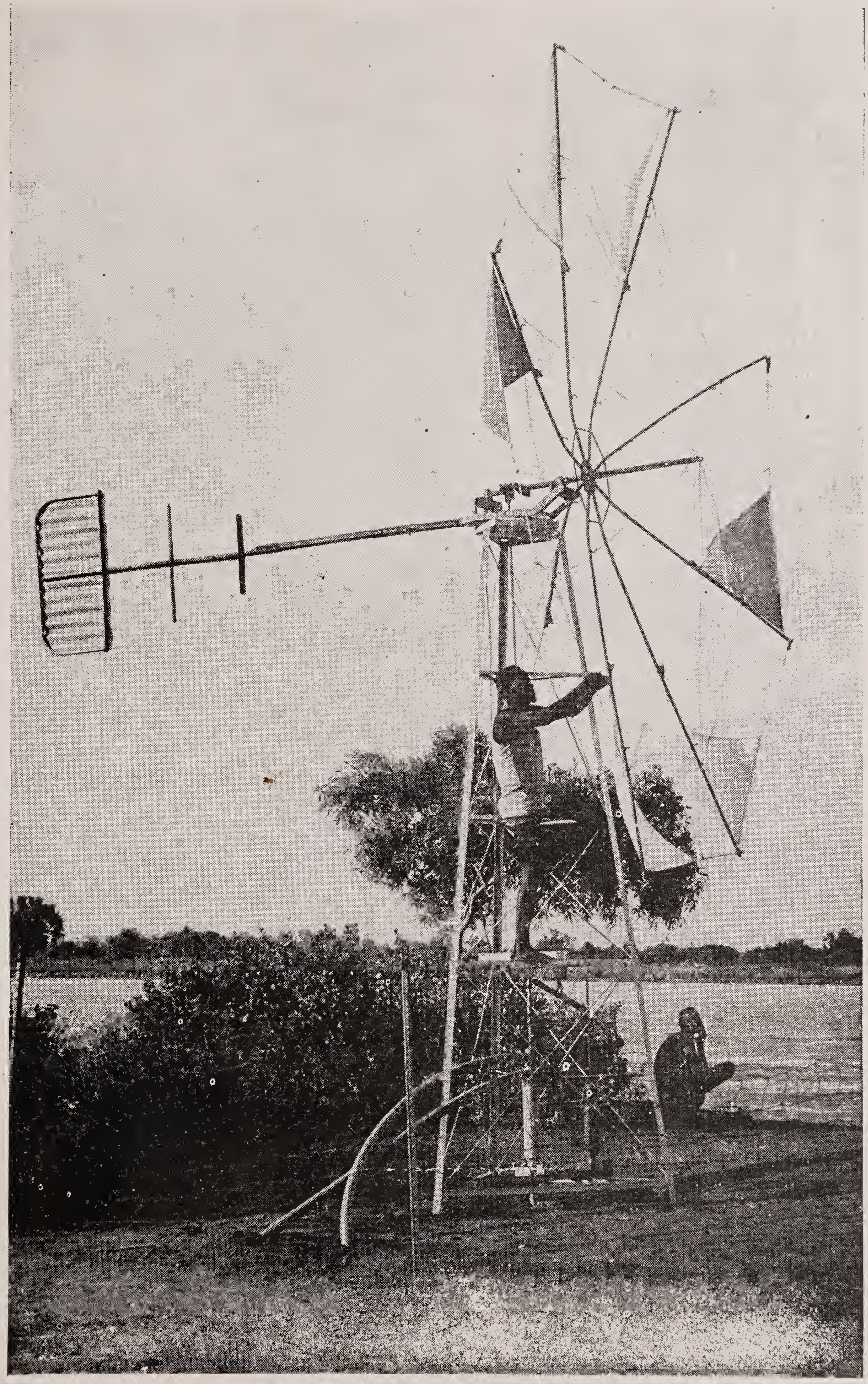

Figure 1. Cretan-type sail windmill fitted with twin single-acting pumps, (to simulate a double-acting pump) under test in southern Ethiopia.

Plate 2

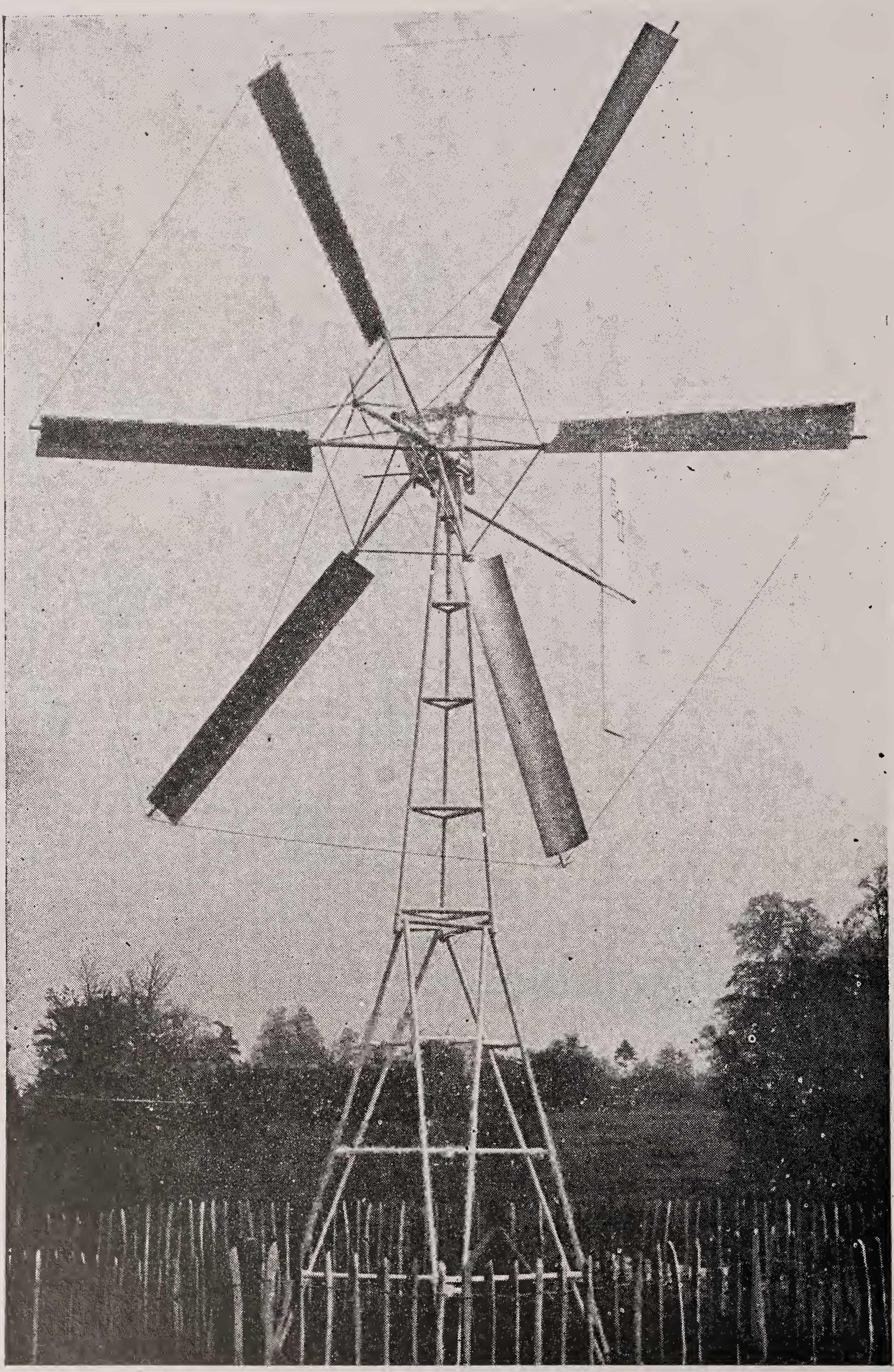

Figure 3. The completed UK prototype windpump; rotor diameter 6 m (20 ft)

Pltae 3

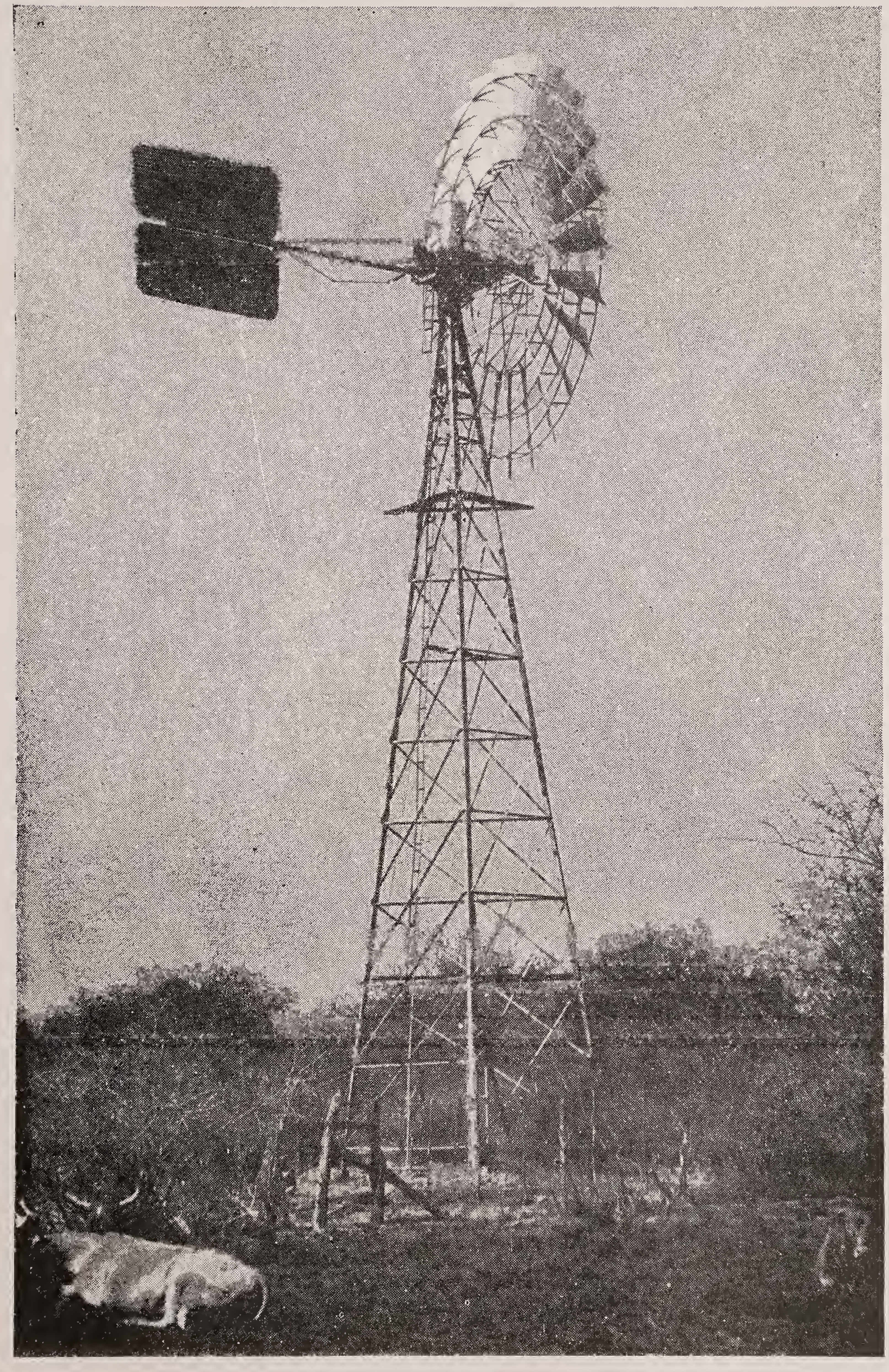

Figure 4. Australian 'Southern Cross' windpump design in use in Botswana. This one has a 27 ft rotor (8·2 m) and is on a 60 ft (18·3 m) tower. Cost was approximately £6000 Sterling (Ca US $12000) in 1976, erected in southern Africa.

A horizontal axis sail windmill for use in irrigation

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Abstract. This paper describes some basic considerations in the design and development of a horizontal axis windmill intended primarily for irrigation in small farms from shallow open wells. This windmill has six triangular sails sweeping a circle of 10 m diameter and is an adaptation from Greek sail windmills. For the construction of this windmill all efforts were made to use materials and parts readily available in the hardware market except for the gear boxes. The cost of material and the parts is Rs. 7,000/- excluding the cost of machining and fabrication. Preliminary performance tests have indicated a pumping rate of 6000–11000 litres/hr over a head of 6·85 m in wind speeds of 10-16 km/hr.

Keywords. Sail windmill; swinging vane rotary pump; bevel gear box; irrigation windmill.

1. Introduction

The water pumping windmill, WP-2, developed in the early sixties at the National Aeronautical Laboratory, Bangalore, has been described by Venkiteshwaran (1962). This windmill has a 4·8 m diameter rotor with twelve galvanised iron vanes. The horizontal axis of shaft rotation is converted into reciprocatory movement along the vertical axis by a slider crank mechanism mounted on the top of a four-legged lattice steel tower. While considering this windmill for irrigation in small farms from shallow dug wells, the following limitations were discovered. A study of wind speed data published by India Meteorological Department (Anon 1931–60) indicates that except for some coastal locations and the eastern part of the country, wind speeds are usually low during the November–March period when much irrigation is carried out in India. For instance, Janardan & Viswanathan (1962) show that at Bangalore, where the annual average wind speed is 13 km/hr, monthly average wind speeds during the November–February period are found to fall in the range of 7–9 km/hr. Their estimations also show that during these four months a windmill sweeping 5·5 m diameter would pump around 330 million litres over a head of 10 m assuming an overall efficiency of 12%. The proportional output of WP-2 would be about 280 million litres since its diameter is smaller. Dakshinamurti *et al* (1973, p. 205) mention an average requirement of 600 mm of water in most parts of the country for non-rice crops. Assuming the average head encountered in practice to be about 10 m, the output of WP-2 would barely irrigate one half hectare. According to Dakshinamurti *et al* (1973, p. 254), using motorised pumps and bullock-powered lifts, 1–4 hectares are irrigated under various crops from open wells in several States. As the output of the WP-2 windmill

is thus smaller than even bullock-powered water lifts, it is open to doubt whether such a windmill would be acceptable in irrigation where the trend is in favour of more powerful pumps. The conventional diesel and electrical pumps, even of smaller sizes of about 3–5 hp, help in reducing seepage losses since the field gets irrigated in about 10–20 hr. Furthermore, the cost of such windmills, estimated to be between Rs 10,000 and Rs 15,000 is rather high, and not many buyers have come forward although it has been in the market for the last five years. This is understandable since a 3–5 hp diesel or electrical pumpset can be procured for about Rs 3,000 to Rs 5,000. While, on a long term basis, the economics of electrical or diesel pumps is not necessarily better compared to the WP-2, a discussion of the subject is beyond the scope of this paper.

It was therefore decided in 1977 to design another windmill with the twin objective of increasing the capacity and reducing the cost. This took the shape of a 10 m diameter windmill (figure 1) using triangular sails—an adaptation of Greek windmills discussed by Sherman (1976, p. 65).

2. Size and design of rotor

Since windmills for irrigation have to be designed to provide full output in low wind speeds, this would result in larger rotor diameters. For instance, if we wish to pump 5000 litres of water per hour over a head of 10 m in a wind speed of 10 km/hr, the rotor diameter should be about 10 m, assuming an overall efficiency of 12%. A study

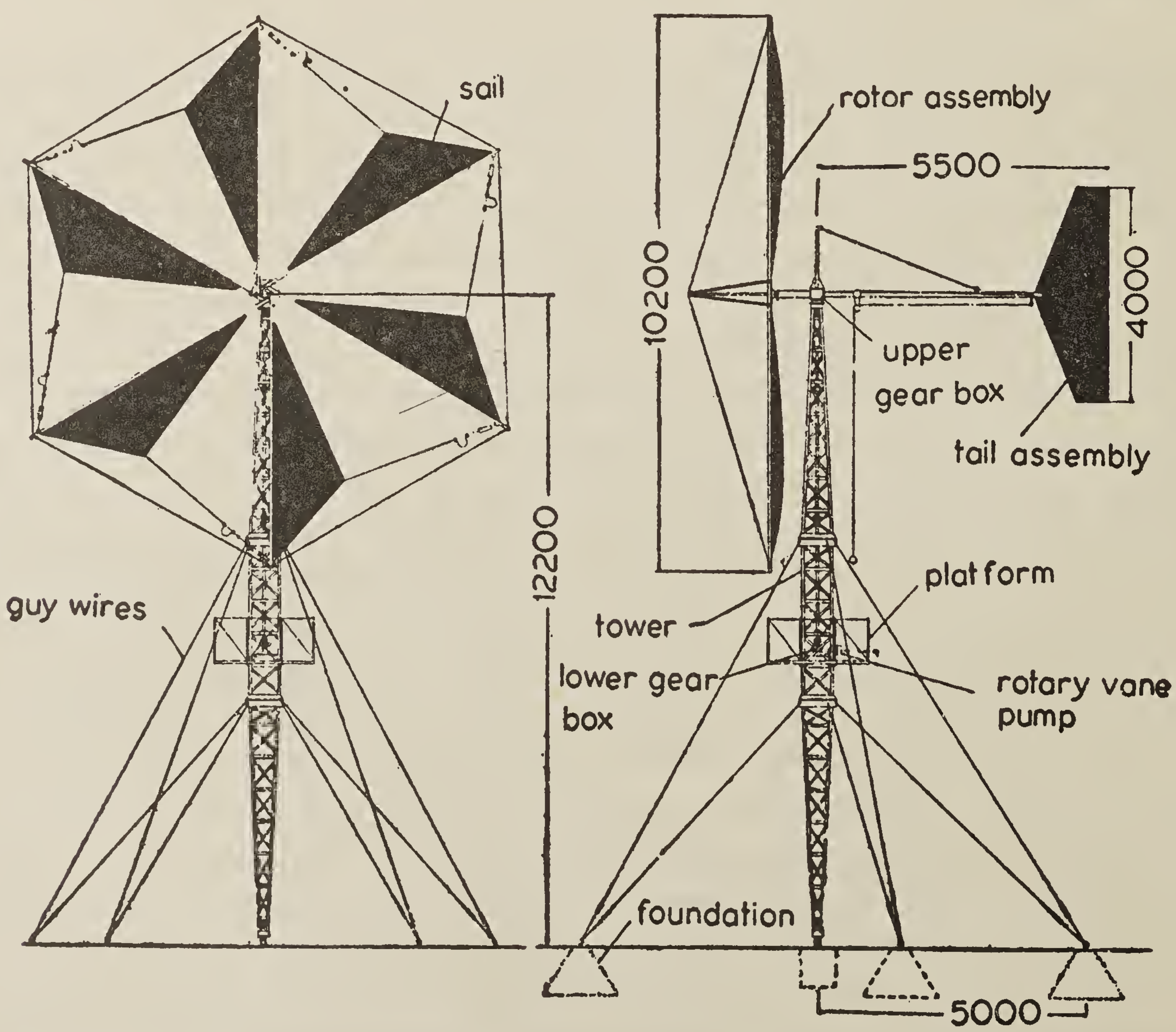

Figure 1. 10 m sail windmill having six triangular canvas sails, guyed tower, and rotary pump mounted under the platform.

of hourly wind speeds records for November–February period for Bangalore indicated that wind speeds equal to and in excess of 10 km/hr were available for nearly 300 hr every month. Neglecting contribution towards water pumping from wind speeds lower than 10 km/hr and assuming output to remain constant at wind speeds exceeding 10 km/hr, a windmill of 10 m diameter and 12% overall efficiency would be able to irrigate an area of one hectare under non-rice cultivation. Such a windmill would irrigate an area comparable to the area irrigated by bullock-powered water lifts and, therefore, would be more suitable than WP-2. While this estimate is based on the wind speed data for Bangalore Airport, one may expect it to be valid where comparable annual average wind speeds namely, 13 km/hr are obtained. Since at 10% of the 235 locations in the country, annual average wind speeds exceeding 13 km/hr have been observed, one can expect this estimate to be valid on a conservative basis at those locations.

If designed in the same manner as WP-2, a 10 m windmill would cost more than that of WP-2. In order to reduce the cost of rotor it was decided to use canvas sails in place of metal vanes. The canvas per square metre basis is estimated to cost less than half the cost of steel vanes, even if the latter happened to be as thin as 1 mm. Besides using low-cost materials like canvas, cost reduction could also be achieved by reducing rotor solidity (defined as the blade or sail area divided by disc area). The high solidity of 0·48 for WP-2 was necessary to obtain low cut-in speed of 8 km/hr with positive displacement pumps. While it is possible to obtain an easier start with such pumps using techniques like reduced pressure at the bottom of the delivery pipe (Shefter 1974, p. 118), this can also be achieved by using rotodynamic or rotary pumps. In the new windmill, swinging vane rotary pumps have been used which permit design of rotor having low solidity. A discussion of the rotary pump is postponed to a later section.

With the choice of a sail-type rotor, it is possible to furl the sails when the windmill is not required to pump water, which is likely to happen during a major part of the monsoon season. Similarly, during the premonsoon months of May and June, when wind speeds are usually high and water is scarce, the sails can be furled. This enables reduction of the wear of various parts, enhancement of the life of sails and reduction in the cost of the supporting structure as well. The possibility of cost reduction in the tower is discussed in a latter section. Manual furling and unfurling of sails may not pose difficult problems as some manpower is usually available in farms.

Sherman (1976, p. 65) gives data about triangular sail windmills in use for decades at Lessithi, Greece and about another windmill which he constructed at Madurai in 1974. However, details of the aerodynamic design of such rotors do not appear to be available. Similarly, design data for the 8 m six sail windmill of Wind Works (Hans Meyer 1977, private communication) are not available. Some data regarding triangular yacht sails have been reported by Marchaj (1971) and Kay (1971, p. 93). An analysis of this information gives a maximum lift-to-drag ratio of 4 at 15° angle of attack and maximum lift coefficient of 1·37, with an aspect ratio of 3. Scaling-up dimensions of the sail of an 8 m rotor of Wind Works in the proportion of 10:8 (figure 2) and applying the aerodynamic data mentioned above, a power coefficient of 0·16 is obtained for a tip speed ratio of 2·0. In the absence of reliable data for sail rotors, no attempt was made to optimise sail dimensions for the new windmill.

The rotor consists of a hexagonal hub plate on which six tubular steel spars of 45 mm outer diameter are mounted as shown in figure 2. The ends of the spars are connected

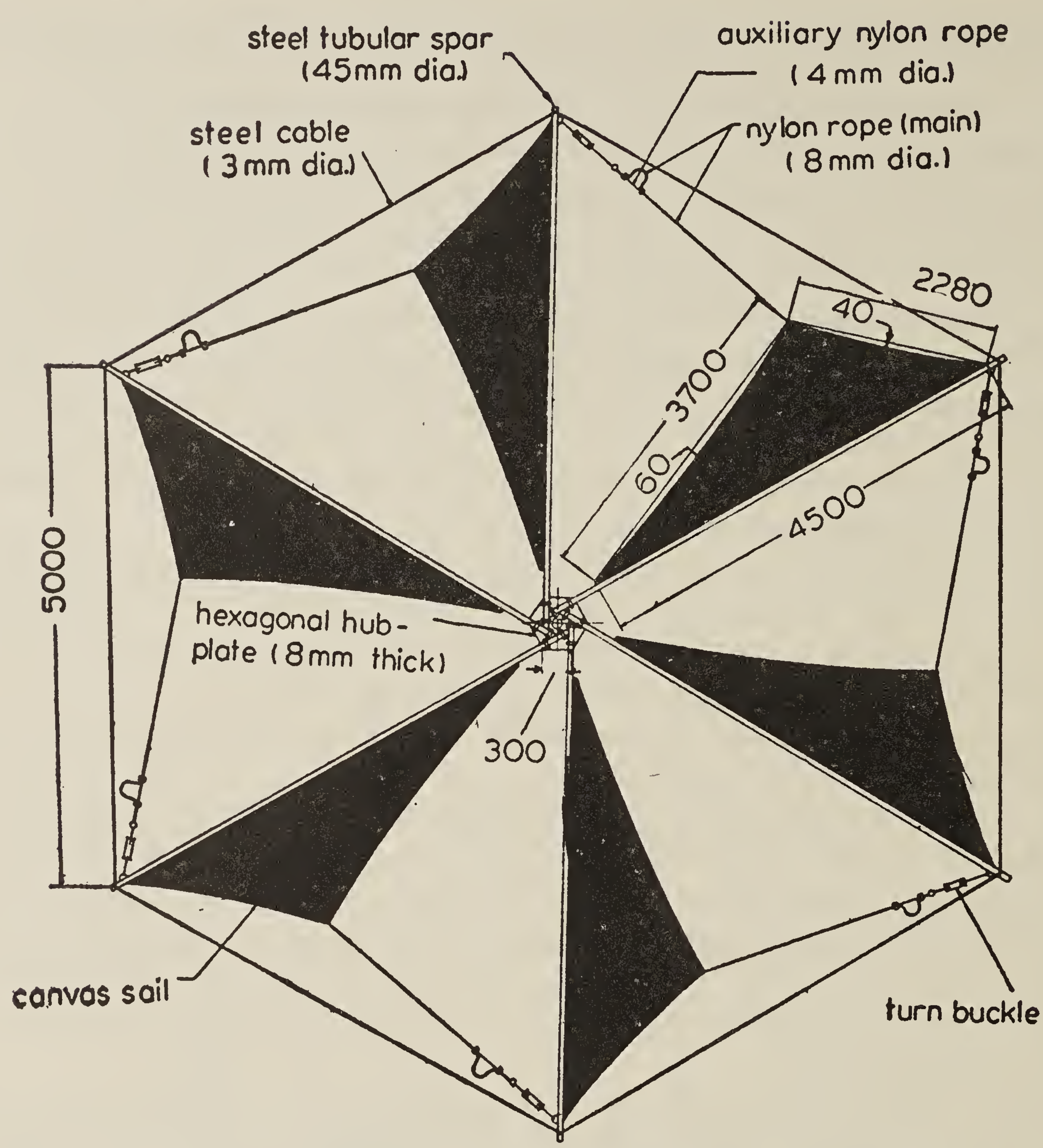

Figure 2. Rotor assembly showing details of sails, safety loops and spars.

by means of steel wire ropes of 3 mm diameter. The rotor has been designed to face the wind ahead of the tower (with a tail at the back). The ends of the spars are also connected through wire ropes to a forward axial projection from the hub plate. This arrangement adds stiffness in the bending mode to the spars when the sails are opened to face the wind. The loose end of the sails is connected onto a hook welded on the next spar by a nylon rope of 8 mm diameter and a turn buckle, as shown in figure 2. As can be seen in figure 2, a loop is made from this nylon rope such that the load from the sail is first transmitted to the next spar through a portion of 4 mm nylon rope. This rope ruptures under a tensile load of about 200 kg. This load is estimated to occur at about 54 km/hr wind speed. Once the thinner rope snaps, the loop gets straightened out and the sail becomes slack. This helps in retarding the speed build-up of the rotor in high winds.

The safety mechanism based on the rupture of thinner rope is expected to protect the rotor from occasional gusts. Gust speeds exceeding 54 km/hr never occurred at Bangalore during November–February for 3 years (1958–1960) as inferred from wind speed charts (unpublished studies made at NAL). During the other months of the year, which are more windy, it would be possible to operate with a reduced diameter, so that the sails could be opened only partially by wrapping them around the mast.

By reducing sail area it would be possible to withstand higher gust speeds. The three-year data for Bangalore indicate that gust speeds exceeded 72 km/hr only 9 times and exceeded 90 km/hr only once. These observations are tentative and an analysis of gust speeds over a longer period is desirable.

A mechanical manually operated band brake is provided on the vertical shaft at the platform level. It is used to stop the rotor to facilitate furling of the sails.

3. Top gear box, power transmission and tail assembly

The rotor of the sail windmill is supported by using a pair of taper roller bearings mounted back-to-back. Figure 3 gives a sectional view of the gear box. The rotor shaft is coupled to a pair of bevel gears to change the axis of rotation of the shaft by 90° and the output shaft is passed through the centre of the tower. The rotor and the bevel gears are mounted at either end of the shaft. The rotor hub is keyed to the shaft which is about 800 mm away from the centre of the output shaft to have sufficient clearance between the rotor spars and the tower. The gear box housing is fabricated by suitably welding steel plates and channel sections. Bearing seatings in the housing are also provided by welding thick steel plates. The bevel gear pair used here is an off-the-shelf item. It provides a step-up speed ratio of 1:2·5. The pinion of the bevel gear pair is supported by a pair of angular contact ball bearings, and the bearing housing is bolted to the gear box casing. The gears and bearings are adequately lubricated.

A lolly column pipe, 110 mm outer diameter and 1 m long, is fixed to the gear box casing and the whole assembly is supported by two cast iron bearings to allow orientation of the rotor in the wind direction. The output shaft is brought down by steel

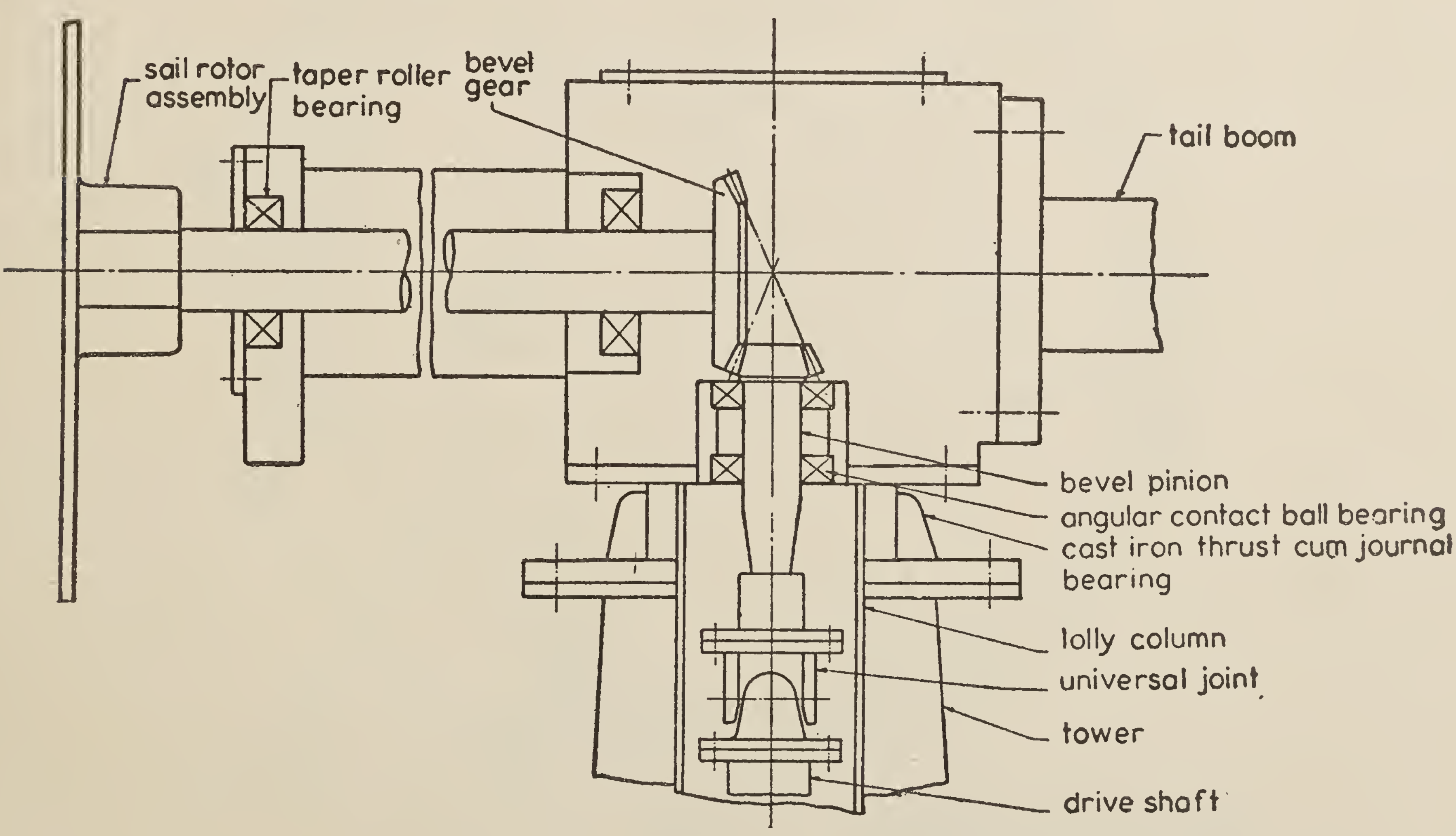

Figure 3. Head mechanism assembly built around a mass produced bevel gear set. Lolly column and cast iron bearings are also shown.

pipe shafting connected with a flexible coupling and a universal joint. The vertical output shaft is guided by self lubrication of the wooden bearings in linseed oil, at about 2 m intervals.

The bottom of the output shaft is connected to a bevel gear box which again turns the axis of rotation by 90° and also provides a step-up of 1:2·5. The horizontal output shaft of the lower gearbox is connected to the pump shaft through a flexible coupling. In a recent arrangement, two pumps were mounted with their shafts in a vertical plane. The drive is provided by roller chains and sprockets replacing the lower gear box. A total step-up of 7·5 has been obtained by this arrangement.

The sail windmill is provided with a tail made from canvas mounted on a framework of conduit pipes. The tail boom is 5·5 m long and the tail vane has an area of 6 sq. m. The tail is provided with a hinge (located close to the tail, not visible in figure 1) around which it can be manually tilted through 30° and locked in position by ropes running parallel to the tail (figure 1).

4. Pump assembly

A commercial, swinging vane rotary pump was selected for use with this windmill.

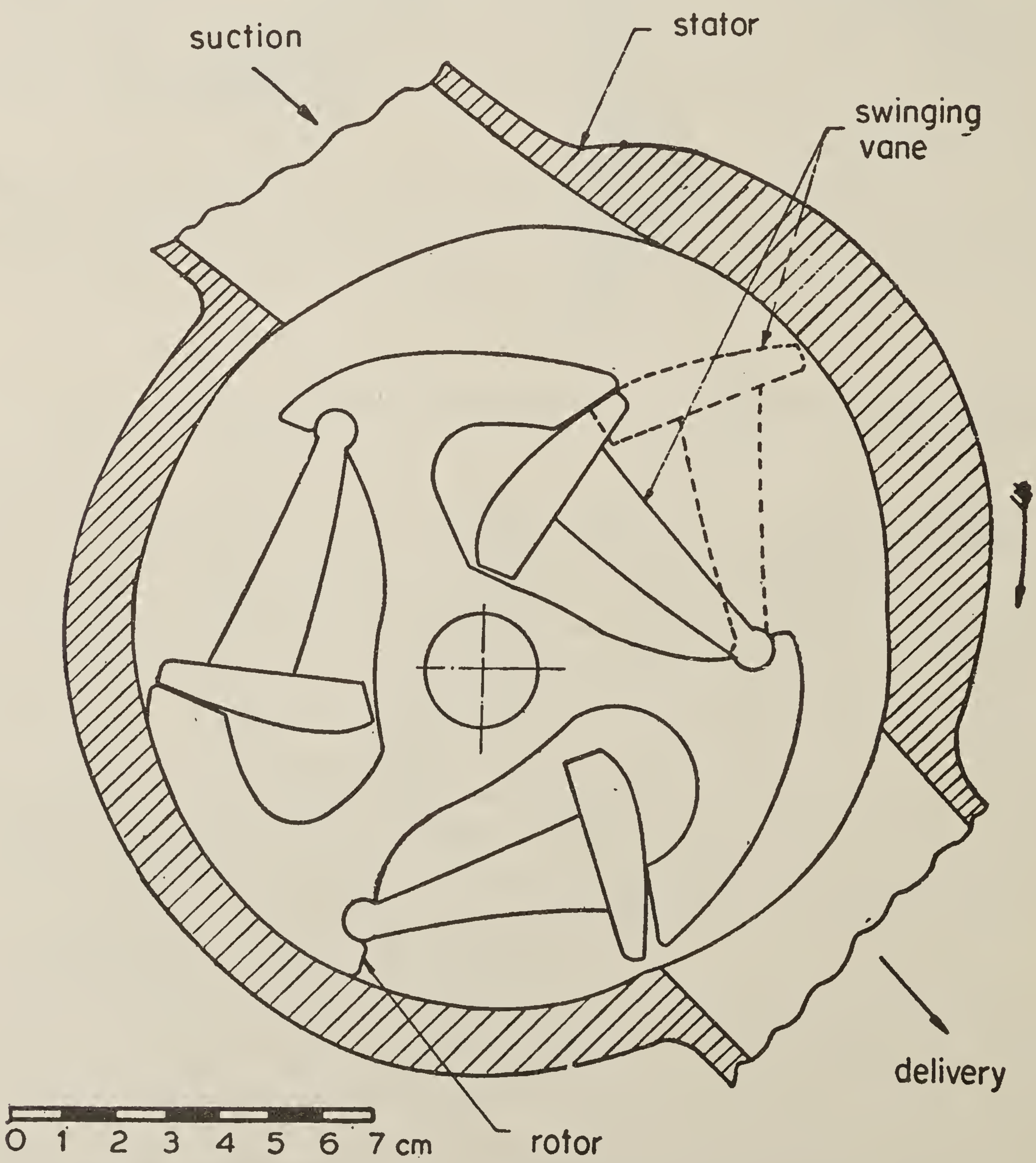

Figure 4. Swinging vane rotary pump (schematic) consisting of three gun metal vanes pivoted on an eccentrically mounted rotor.

This pump has three gunmetal vanes which swing about their hinges on the pump rotor as shown in figure 4. The pump rotor is mounted eccentrically within the stator body. The effectiveness of the pumping depends upon the contact pressure between the swinging vane and the stator body. At a low speed of rotation, this pressure is lower and the discharge is also proportionately low. As shown in figure 5, below a certain speed of rotation the discharge is practically zero. Thus, this pump does not load the windmill at low rotational speeds, permitting the windmill rotor to start at lower wind speeds. By using this pump, the windmill could be started at wind speeds of 7 km/hr (figure 6) yet keeping a low solidity of 25% on the rotor.

5. Design of tower

Hütter (1973, p. 206) states that an optimal windmill would use the shortest possible tower. However, a minimum clearance of about 3 m between the tip of the blade and the ground is desirable to minimise the possibility of injury to people working near the windmill. For the prototype it was decided to design a tower, 12 m high, so as to mount the pump on the tower at a height of about 6 m from the ground.

For WP-2, a four-legged, free-standing tower was used; but for the new windmill, guyed towers were chosen. A windmill tower experiences 3 categories of loads, one of which is vertical and the other two, horizontal. The vertical load, which can be taken to be independent of wind speeds, is due to the weight of the rotor, the tail and

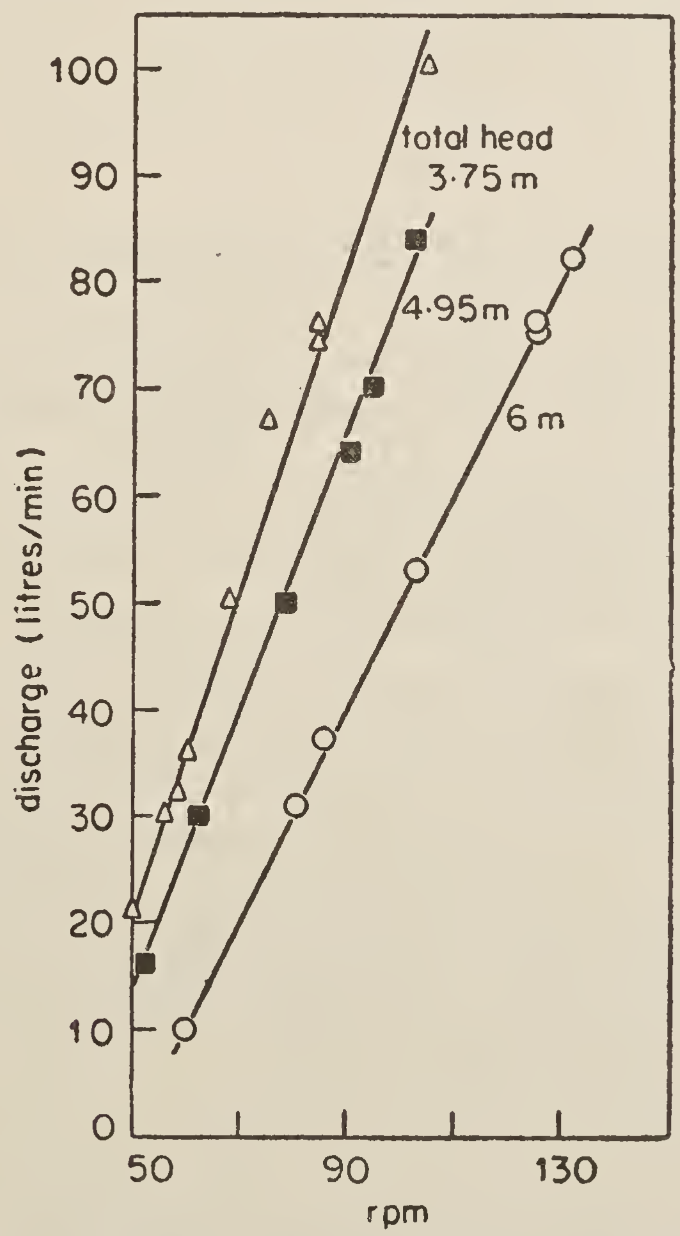

Figure 5. Characteristics of rotary pump at low heads showing threshold speeds for operation.

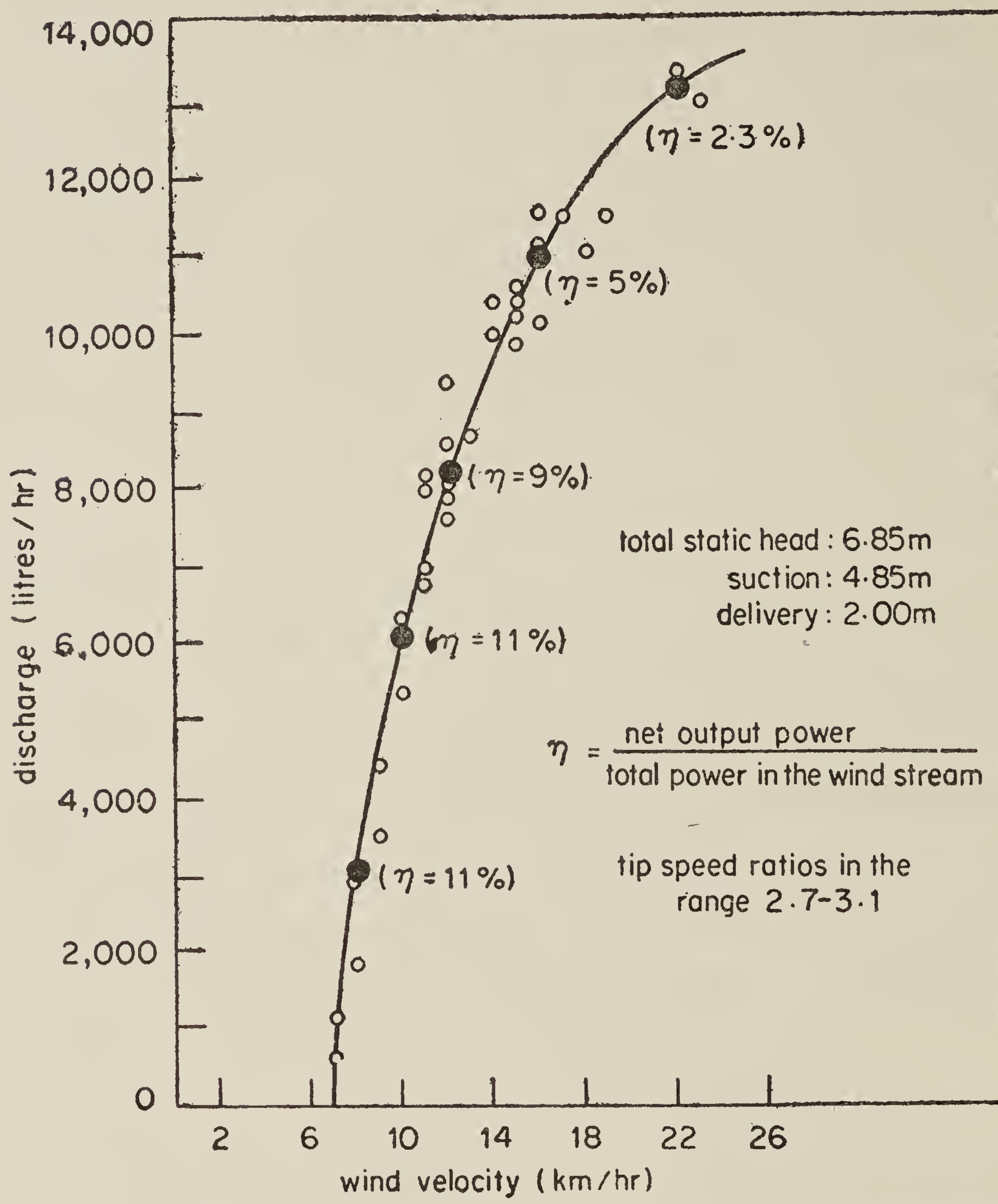

Figure 6. Performance in low wind speed for a given head with two pumps.

the head assembly. Of the two horizontal loads, one is due to the drag caused to the windflow by the tower. The other horizontal load, which is due to the windmill rotor, is directly proportional to the rotor area and the square of the wind speed. Arvindakshan & Ramanathan (1962) designed a four-legged, free standing tower of 10 m height for the WP-2 windmill for a horizontal load of 860 kg and vertical load of 550 kg. The maximum force experienced by the critical members (anchor posts) due to wind force acting on the rotor was an order of magnitude higher than the force experienced by these members due to vertical loads. The magnitude of the horizontal wind force transmitted to the anchors can be reduced by increasing the taper angle (6° 10 ft in WP-2 tower). Using a guyed configuration this taper angle can be increased to a value as high as 30° to 45° (as used in the sail windmill tower, figure 1). In guyed towers, horizontal wind loads acting on the rotor are almost entirely resisted by the wire ropes. The main column can then be designed to withstand compression under the dead load and the vertical components of tension in guy ropes. By designing the central column to resist vertical loads and wire ropes to bear horizontal loads some savings can probably be expected, although such a claim is not made for the tower shown in figure 1. This tower is a combination of a free-standing tapered tower (the portion above the wire ropes) and a guyed tower (the portion below the wire ropes). This combination was necessary as it was not

possible to draw wire ropes from the top, which would have either interfered with the free movement of the rotor or resulted in higher costs.

6. Costs

An estimate of parts which were bought and used in the fabrication of the prototype is given in table 1.

Table 1. A list of components used in the prototype and their costs.

	Rupees
Rotor: tubes for spar, 3 mm wire ropes, nylon ropes, turn buckles, clamps, and canvas	1,500
Tail: tail pipe, conduits, canvas	300
Top gear box: gears, lolly column, bearings, cast bearings for lolly column	800
Bottom gear box and power transmission: gears, bearings, shafting, universal joint, flexible couplings	900
Tower: angle sections, wire ropes, eyebolts, turn buckles, clamps	1,600
Pump: swinging vane, rotary pumps (2 nos.)	1,600
Foundation	300
Total	7,000

The cost of labour and machine hours used in the fabrication of gear boxes and other parts could not be estimated during the construction of the prototype.

7. Performance of the windmill

The windmill was tested during June and July using two rotary vane pumps coupled to the vertical output shaft by chains and sprockets. Separate suction and delivery piping connections were made for both the pumps and on the delivery side of the piping, water meters were installed to measure the discharge. The pumps were operated under a suction head of 4·85 m and a delivery head of 2 m giving a total static head of 6·85 m. To evaluate the performance of the windmill, the following parameters were measured: the wind velocity, the rotational speed of the rotor and the rate of discharge. The results are given in figure 6, which shows the plot of discharge against wind velocity. The cut-in speed with the present arrangement appears to be 7 km/hr. The tip speed ratio in the wind speed range of 7–22 km/hr is about 2·9. The efficiency of the windmill at different wind velocities is also shown in figure 6. Maximum efficiency is attained at a value of 11 % in the wind speed range of 7–12 km/hr. This somewhat lower efficiency coupled with the high tip-speed ratio of 2·9 suggests that the rotor is not optimally loaded. This could be examined by increasing the static head for water pumping in subsequent performance tests.

8. Future programmes

From the experience of prototype construction and performance tests, it is proposed to carry out the following modifications.

(i) simplify the construction of top gear box which required expensive machining in the prototype construction;

(ii) instal the mechanical brake on the main rotor shaft itself as its present location on the vertical shaft is not satisfactory. The mechanical brake will be operated from the platform;

(iii) design an automatic regulation system using springs and dampers along with a side vane, as the present manual arrangement of turning the tail by 30° from the wind direction does not effectively slow down the rotor;

(iv) reduce the height of the tower from 12 m to 8 m, as the present tower, being somewhat high, would make it difficult for a farmer to climb up to the platform to furl and unfurl the sails;

(v) design and fabricate a new pump to replace two pumps in the present prototype. These commercially available pumps were originally designed for oil pumping and moreover, two of them were required to load the windmill. While designing the new pump suitable materials will be used to reduce wear. Water itself will be used as the lubricant for the sliding vanes and the bearings.

The design, construction, erection and testing of the prototype would not have been possible without the enthusiastic support of the staff members of NAL in various divisions, especially the Engineering Services. Dr S R Valluri, Dr M A Ramaswamy and Mr K Venkatachalam offered a number of suggestions during the design and fabrication of the prototype, and to them we express our thanks.

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Prospects for wind energy utilisation in Karnataka State

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Abstract. An examination of the data available at 22 meteorological stations in Karnataka State shows that wind velocities in the State as a whole are neither spectacularly high nor negligibly low. The highest winds (annual mean of around 13 km/hr) are experienced in parts of the northern maidan region of the State (Gulbarga, Raichur and Bidar districts) and in Bangalore. The winds are strongly seasonal: typically, the five monsoon months May–September account for about 80% of the annual wind energy flux. Although the data available are inadequate to make precise estimates, they indicate that the total wind energy potential of the State is about an order of magnitude higher than the current electrical energy consumption.

The possible exploitation of wind energy for applications in rural areas therefore requires serious consideration, but it is argued that to be successful it is essential to formulate an integrated and carefully planned programme. The output of current windpumps needs to be increased; a doubling should be feasible by the design of suitable load-matching devices. The first cost has to be reduced by careful design, by the use of local materials and skills and by employing a labour-intensive technology. A consideration of the agricultural factors in the northern maidan region of the State shows that there is likely to be a strong need for mechanical assistance in supplemental and life-saving irrigation for the dry crops characteristic of the area. A technological target for a windmill that could find applications in this area would be one with a rotor diameter of about 10 m that can lift about 10,000 litres of water per hour in winds of 10 km/hr (2.8 m/s) hourly average speed and costs less than about Rs 10,000. Although no such windmills exist as of today, the authors believe that achievement of this target is feasible. An examination of various possible scenarios for the use of windmills in this area suggests that with a windpump costing about Rs 12,000, a three hectare farm growing two dry crops a year can expect an annual return of about 150% from an initial investment of about Rs 15,000. It is concluded that it should be highly worthwhile to undertake a coordinated programme for wind energy development that will include more detailed wind surveys in the northern maidan area (as well as some others, such as the Western Ghats), the development of suitable windmill designs and a study of their applications to agriculture as well as to other fields.

Keywords. Wind energy; Karnataka State; energy resources; economics of windpumps; load matching for windpumps.

1. Introduction

The growing energy crisis facing the world has led to a search for new sources of energy, and to a re-examination of some older ones: among the latter is the wind, which has been exploited for thousands of years, beginning with the use of sail to drive boats and ships and (later) of mills to grind corn or lift water. Sometime in the first half of this century it appeared as if the wind as a source of energy had 'finally' declined in importance. The recent revival of interest in its possibilities—due largely to the phenomenal increase in the cost of more conventional sources

of energy, and to the realisation that global reserves of fossil fuel are limited—demands a brief look at the chequered history of efforts to exploit the wind.

From the fascinating account given by Derry & Williams (1960), we learn that windmills probably first appeared in West Asia around the 7th century A.D., and were used for irrigation particularly in Persia. They are thought to have reached Europe through Moorish Spain, but somewhere during this migration the axis of rotation changed by 90°—Asian windmills turned round a vertical axis, but European machines have invariably been of the horizontal axis type (till the inventions of Savonius and Darrieus in the 20th century). The famous windmills of Holland, which produced about 10 kW with a 10 m rotor in 30 km/hr (8·3 m/s) winds, helped drain much of the land reclaimed by the Dutch from the sea. Derry & Williams believe that windmills of this type were the prime movers that ushered the industrial revolution. With the advent of steam power windmills lost their importance in Europe, but reappeared in a slightly different version among the vast open spaces of the New World. In 1850, windmills are estimated to have produced about 10^9 kWh ($3{\cdot}6 \times 10^{15}$J) in the USA (Clark 1977). The new version was the multi-bladed metal type, still familiar in many parts of the world; typically a 4 m rotor of this type delivers about a kilowatt in 30 km/hr (8·3 m/s) winds. By 1880, the 'twenty-five-dollar windmill' had finally become a reality (Bartlett 1974); and the mature industry that developed to manufacture these machines fell into rapid decline only after the 1930s in the US, when President Roosevelt set up a Rural Electrification Administration to provide subsidised electric power to the American farmer (Clark 1977). Even then, Dempster of USA still used to sell 10,000 windmills a year in the 1940s (Merriam 1972); and it is estimated that there were more than 0·6 million windmills operating in the world by the end of the last decade (Shefter 1972).

It has been suggested (Derry & Williams 1960) that the windmill came early to India from West Asia, but we know of no strong supporting evidence. In an India Meteorological Department (IMD) Scientific Note (IMD 1948), there is reference to a paper by Griffith, who in 1895 considered windmills as having no future in India. On the other hand, only a few years later (in 1903) Sir Alfred Chatterton was strongly advocating their use, after trials he conducted in Madras. A systematic attempt to introduce wind machines in India was made by the National Aeronautical Laboratory during the 1950s and 60s (Sen Gupta 1966).

In spite of all these efforts, however, the windmill has never gained a secure foothold in India. This raises two questions. Are there fundamental reasons why wind energy has remained untapped in India? Has the energy crisis now changed the picture substantially?

The answers* to these questions are to be sought in

(i) the nature and magnitude of the available resources;
(ii) the technologies available for their exploitation;
(iii) the economics of exploitation, particularly in relation to competing energy sources (which in India would not only be electricity, coal, oil, etc., but also muscle power, both human and animal).

*In handling such large issues sociological questions are undoubtedly relevant, but it is not our purpose to go into them here.

We consider each of these in turn, with particular reference to the possibilities for exploitation of wind energy in Karnataka State. Although the scope of the study is thereby (intentionally) limited, it is expected (for reasons that will become clear as we proceed) that our conclusions may be valid for many other parts of India as well.

The current revival of interest in wind energy may be partly attributed to certain well-known advantages. It is 'free' and renewable; where it is at all feasible to tap it, it is fairly widely distributed, so that power can be generated right where it is needed (of course if wind is used for large scale electric power generation distribution costs would have to be taken into account). The technology for extracting energy from the wind is largely already available, and may even be made accessible to rural areas. Furthermore, the wind is fairly reliable; for example, we calculate from meteorological data for Bangalore that the coefficient of variation of the mean annual wind speed is only 5·7 %, whereas the coefficient of variation of rainfall is 23 %. Finally, wind energy is pollution-free.

On the other hand, wind energy suffers from the serious disadvantage that its energy density is low (it is 60 J/m^3 at 10 m/s; petrol contains 30×10^9 J/m^3!). One consequence is that large structures are needed to extract reasonable amounts of energy, and the first cost of windmills tends to be high. Finally the wind, even if relatively reliable over a period of about a month, is intermittent over shorter periods.

Any success that may be achieved in utilising wind energy will have to overcome these disadvantages. Clearly, the problems are going to be: how to reduce first cost by ingenious design, how to increase power output for given first cost, and how to store energy efficiently and inexpensively to tide over 'lulls' in the winds. Our attention will be focussed on possible applications of windmills in rural areas, in particular for pumping water, which has often been noted as a key requirement (Reddy & Subramanian 1979).

2. Wind energy resources of the State

2.1 *Wind data*

The only source of data on winds in the State is the India Meteorological Department; these data comprise (Iyer 1973)

(i) continuous wind speed records at three observatories (two at Bangalore, the third at Mangalore Harbour);
(ii) daily mean speeds, hourly means at 0830 and 1730 hr, and the mean between these two hours, at 22 stations spread over the State;
(iii) additional hourly mean speeds at selected three-hour intervals starting at 0230 hr at five of the 22 stations (Bangalore, Bangalore Airport, Belgaum Airport (Samra), Gadag and Mangalore Airport (Bajpe)).

The stations at which data are available are shown on a map of the State in figure 1. The annual average speeds obtained from these records are listed in table 1.

Unfortunately these stations are often in the centre of towns or cities, where the winds are strongly affected by the local terrain and the surroundings, and may not be

Table 1. Yearly mean wind speeds at the meteorological stations in Karnataka

District	Station	Yearly mean speed km/hr (m/s)	Height of the anemometer (m)	Hours of observation*
Met. Sub-Division: *Coastal Mysore*				
1. N. Kanara	Honavar	5·4 (1·5)	—	b
2.	Karwar	9.5 (2·6)	6·9	b
3. S. Kanara	Bajpe(A)	7·2 (2·0)	—	g
4.	Mangalore	8·4 (2·3)	16·2	b
5.	Mangalore Harbour	— —	—	h
Met.Sub- Division: *Interior Mysore, North*				
6. Belgaum	Samra(A)	9·7 (2·7)	—	e
7.	Belgaum	9·3 (2·6)	12·6	b
8. Bidar	Bidar	13·3 (3·7)	10·8	b
9. Bijapur	Bijapur	8·3 (2·3)	9·6	b
10. Dharwar	Gadag	11·4 (3·2)	9·6	f
11. Gulbarga	Gulbarga	13·2 (3·7)	10·8	b
12. Raichur	Raichur	13·0 (3·6)	12·3	b
Met. Sub-Division: *Interior Mysore, South*				
13. Bangalore	Bangalore(A)	13·7 (3·8)	—	c, h
14.	Bangalore	11·5 (3·2)	16·5	d, h
15. Bellary	Bellary	8·4 (2·3)	9·7	b
16. Chikmagalur	Balehonnur	5·0 (1·4)	5·1	a
17. Chitradurga	Chitradurga	9·4 (2·5)	7·8	b
18. Coorg	Mercara	11·0 (3·0)	5·4	b
19. Hassan	Hassan	9·3 (2·6)	10·2	b
20. Mysore	Mysore	10·6 (2·9)	21·9	b
21. Shimoga	Shimoga	5·3 (1·5)	—	b
22.	Agumbe	4·7 (1·3)	—	a

Hours of observation*

a			0830					
b			0830			1730		
c		0530	0830	1130		1730		2330
d	0230		0830	1130	1430	1730	2030	
e		0530	0830	1130	1430	1730	2030	
f		0530	0830	1130	1430	1730	2030	2330
g	0230	0530	0830	1130	1430	1730	2030	2330
h	Continuous recording using Dines Pitot Tube Anemograph.							

A: Airport
**Hourly observations are based on 3-minute averages

sufficiently representative of the conditions away from urban areas. Furthermore, the height at which the wind is measured is not the same in all stations as data from IMD (1966) show. The data therefore cannot be used for a strict comparison of one station with another, and as Golding (1962) has pointed out, are only of limited value for wind power studies. More detailed wind surveys that provide continuous records at standard heights are therefore essential. This is in particular necessary for identifying possible sites where large scale wind power exploitation

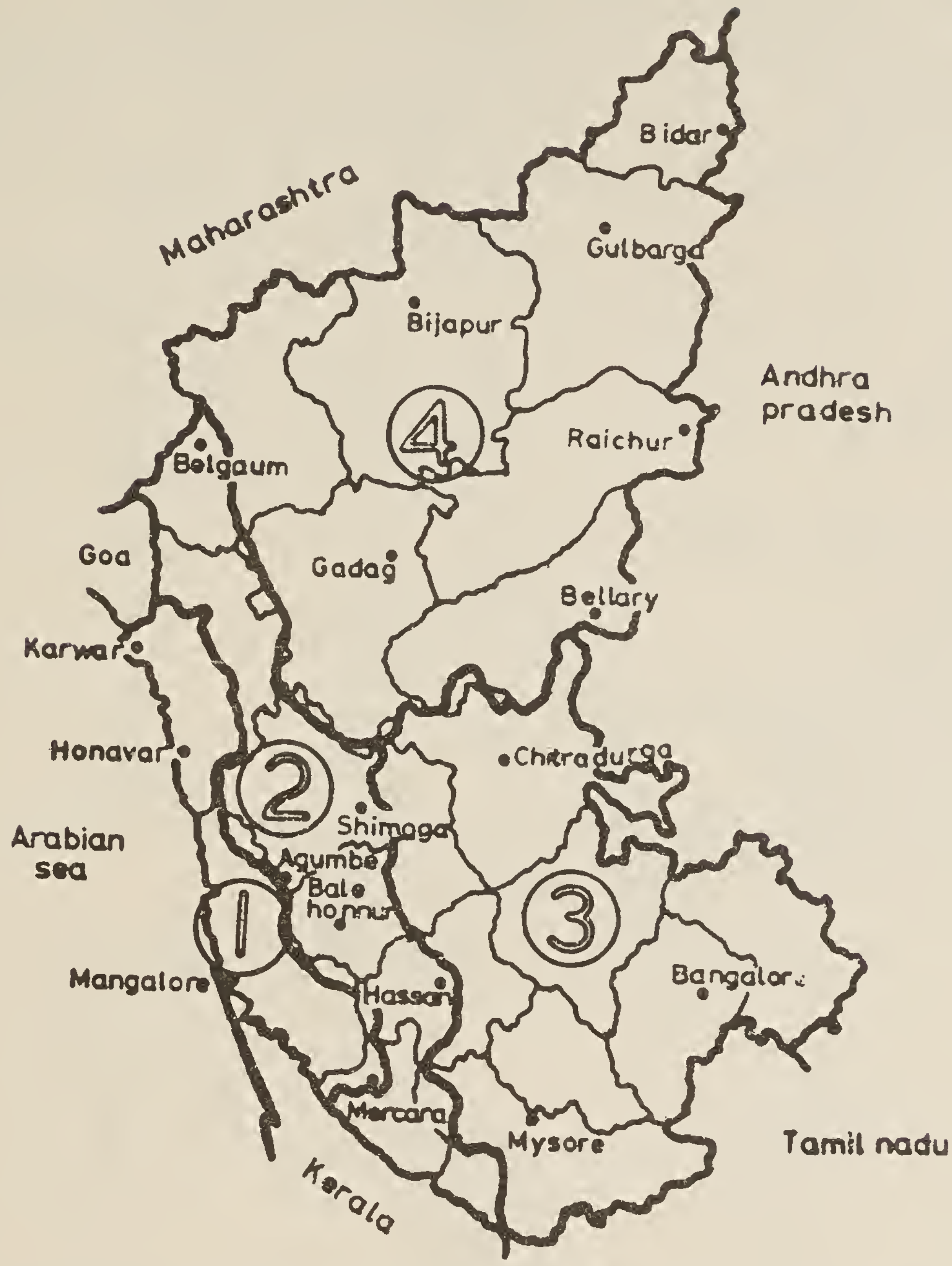

Figure 1. Meteorological stations and geographical regions of Karnataka: 1. Coastal plain, 2. Malnad region, 3. Southern maidan, 4. Northern maidan

may be attractive, as it is not unlikely that there will be sites in the hilly areas of the State at which wind speeds are far higher than those listed in table 1. (For example, recent observations at Raichur (1980, unpublished) have shown steady high winds of about 25 km/hr (6·9 m/s) for several hours during night even in February, which is generally a lean month (see § 2.2).)

Nevertheless, the data available do provide a good starting point for a preliminary assessment of the total wind energy potential in the State. That the wind velocities in the State cannot be considered very high or very low is evident from table 2, where data for some regions where windmills have at some time been in widespread use are shown.

2.2 *Seasonal and geographical patterns*

The State is normally divided into four geographically distinct regions (Learmonth & Bhat 1961): the coast, Malnad (='hill country'), and the northern and southern maidans (=plains); these regions are also shown in figure 1.

The monthly mean wind speeds at the stations listed in table 1 are plotted in figures 2a and 2b. The graphs for various stations seem to fall into three clusters as follows.

Mangalore, Honavar and Shimoga record generally very low wind speeds. Ac-

Table 2. Comparison of wind speeds of different regions

Country (and location)	Annual mean wind speed km/hr (m/s)	Height of the anemometer (m)
1. Netherlands	19 to 32 (5·3 to 8·9)	
2. Denmark	22 to 31 (6·1 to 8·6)	Not known but is likely to be 10 m from the ground
3. United Kingdom	16 to 42 (4·4 to 11·7)	
4. Southern Germany	16 (4·4)	
5. France	13 to 25 (3·6 to 6·9)	
6. India		
6.1 Sagar Islands (West Bengal)	19 (5·3)	15·6
6.2 Puri (Orissa)	18 (5)	8·7
6.3 Rajkot (Gujarat)	18 (5)	9·3
6.4 Bangalore Airport (Karnataka)	14 (3·9)	—
6.5 Bangalore (Karnataka)	12 (3·3)	16·5
6.6 Balehonnur (Karnataka)	4 (1·1)	5·1

Sources: Tewari and Srinath (1975) and Anon (1966).

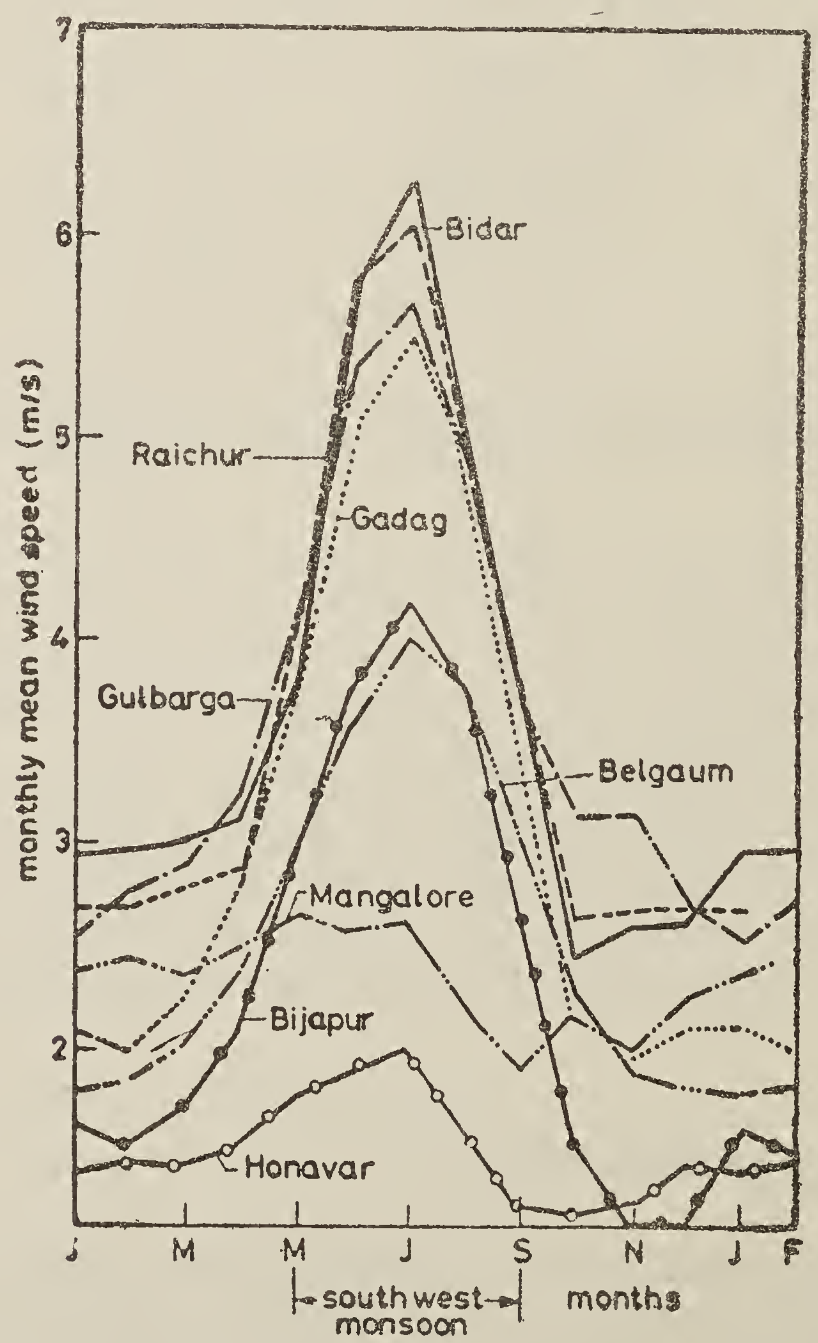

Figure 2a. Variation of monthly mean wind speed.

cording to IMD (1965), Karwar and Balehonnur also have similar winds. These stations are in the coastal and Malnad regions of Karnataka (figure 1).

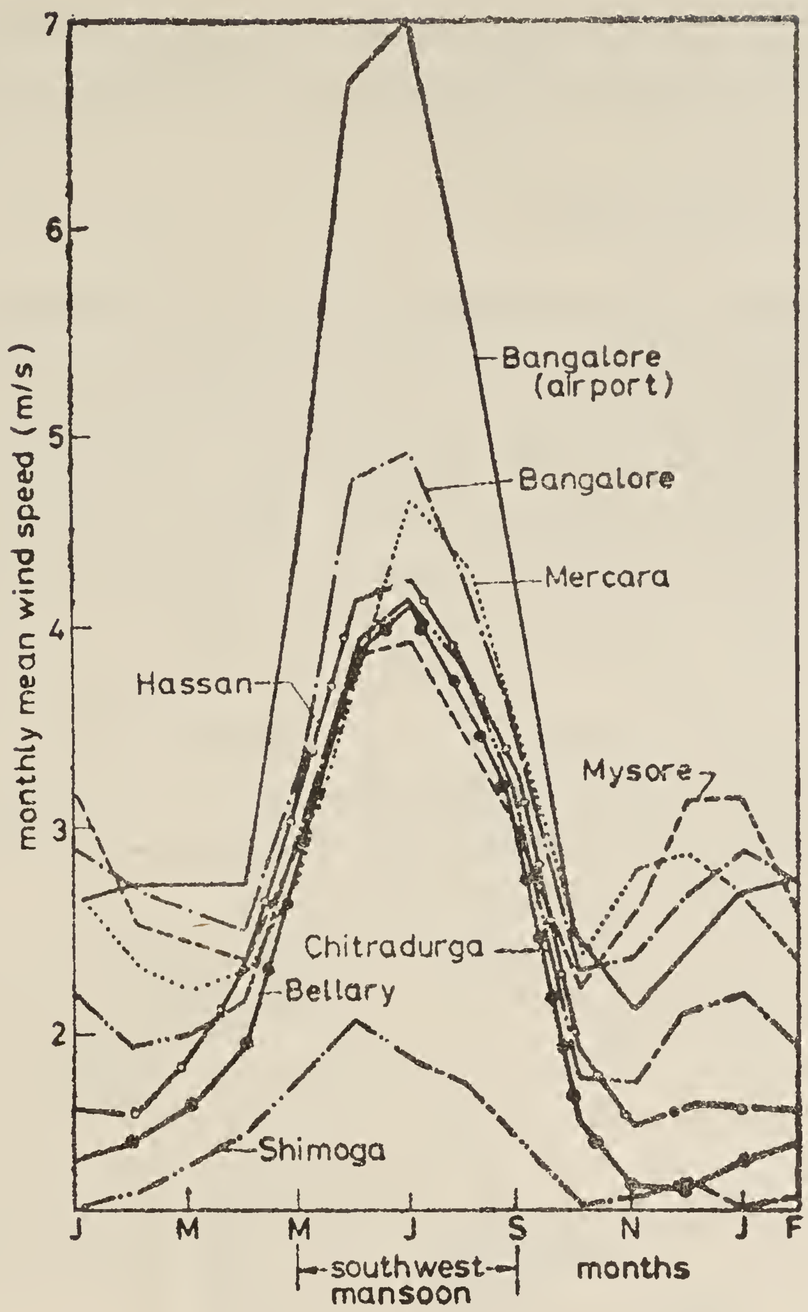

Figure 2b. Variation of monthly mean wind speed.

The second cluster consists of stations at Bidar, Gulbarga, Raichur, Gadag and Bangalore Airport. These record wind speeds of about 20 km/hr (5·6 m/s) during the south-west monsoon. Except Bangalore Airport, these stations are located on the northern maidan.

The rest of the stations seem to experience winds of about 15 km/hr (4·2 m/s) during the south-west monsoon.

There seems to be very little wind (monthly mean of about 10 km/hr (2·8 m/s) or less) after September, though some stations (mostly those to the east) record a slight increase in the wind speeds during December, probably due to the north-east monsoon.

Thus, for windmill applications it would appear that the winds may be considered reasonably good during the south-west monsoon in the northern maidan and in Bangalore and nearby areas. They are likely to be mostly poor on the coastal plain and in the Malnad region. Elsewhere in the State wind speeds are not good, but may be useful under certain conditions.

It is necessary to stress here that the geographical patterns arrived at are based on the data from only 22 stations in the entire State. Therefore the existence of specially windy sites at least in some parts of the State cannot be ruled out, but separate surveys will be necessary to identify them. In any case, it will be assumed for the purpose of this paper that the annual mean wind speeds measured at the meteorological stations are valid for the entire district in which each station is located. For

Tumkur and Kolar* and also for the district of Bangalore itself, the wind speeds at Bangalore Airport will be used. For Mandya the wind speed at Mysore will be used.

2.3. *The energy content of the wind*

A wind stream of speed V has an energy flux of $\frac{1}{2}\rho V^3$, which at normal temperture (30°C) amounts to about $0\,013V^3$ W/m^2 if V is in km/hr (and $0{\cdot}6V^3$ W/m^2 if V is in m/s). However, the total energy in a fluctuating wind is often considerably higher than the energy estimated by this formula if V is taken as the mean wind speed; the reason is that the energy content at higher wind speeds is disproportionately more than at lower speeds. The energy in the mean wind has therefore to be multiplied by a so-called energy pattern factor (EPF) to obtain the total energy content. The value of this factor at different places listed in table 1 is not known in general; but for Bangalore and Belgaum, on the basis of *hourly* mean wind speeds, Golding (Ramakrishnan & Venkiteshwaran 1961) has obtained a value of 3·4 to be used with the *annual* means. (Golding actually quotes a value of 2 for the EPF,

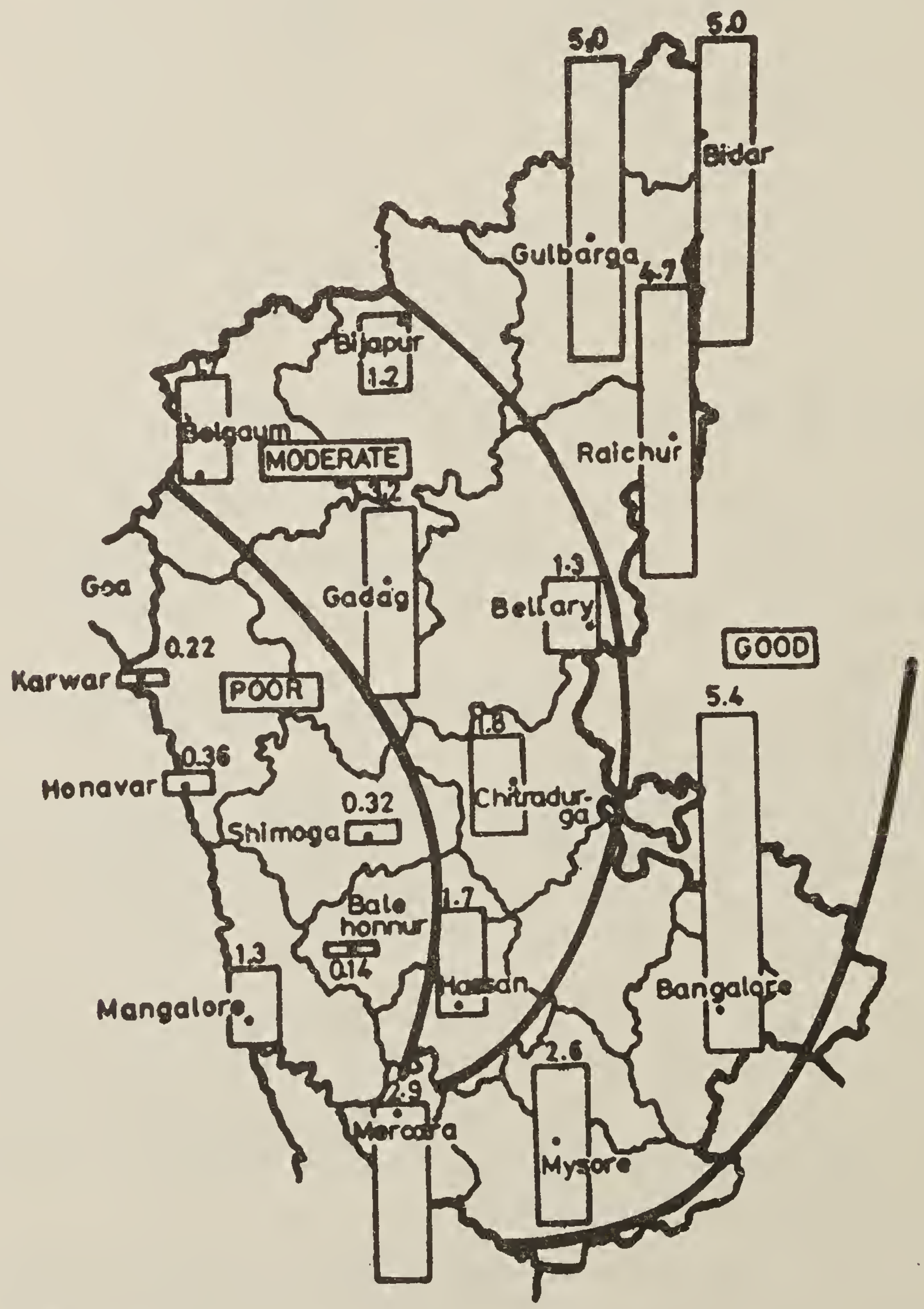

Figure 3a. Annual wind energy flux. Maximum monthly mean wind speed km/hr (m/s)—poor 0(0) to 10(2·8); moderate 10(2·8) to 15(4·2); good 15(4·2) and above.

*No data are available for Tumkur and Kolar; the present conjecture for these districts is based on geographical proximity to Bangalore and the general similarity in vegetation cover and rainfall patterns.

but this takes into account the Betz value of the limiting efficiency (~59%). The value quoted here is merely 2/0·59.) Using this value and the results from certain preliminary measurements at the Indian Institute of Science campus (Rajagopalan 1978), the *annual* energy pattern factor, including variations on the scale of seconds, is estimated by us to be roughly 5·5 (Shrinivasa *et al* 1978). (Note that this value of EPF is appreciably higher than in more temperate climates, where the atmosphere is less gusty than in a tropical country like India.) Assuming this factor to be valid at other stations also, an estimate of the total wind energy flux at each of the 22 stations in table 1 has also been made and is presented in figures 3a and 3b. It can be seen from figure 3b that at most of the stations nearly 80% of the annual wind energy flux is concentrated in the southwest monsoon period of May to September.

2.4. *Permissible windmill area*

If there are a large number of windmills in a given area there will be a reduction in the power generated by most of them due to wake interference. Rangi *et al* (1974) state that '... theoretical calculations of the retarding effect of the windmills on the earth's wind layer indicate that if their spacing is closer than 30 diameters, there is a fairly sharp reduction in the power available from each windmill...'. This spacing of 30 diameters when expressed as a ratio of total windmill area to the ground area turns out to be about 0·1% and was used by them to map the wind power potential of Canada.

Assuming a 10% loss in power due to interference as above, Newman (1977) also arrives at a figure of 0·1% for the area density.

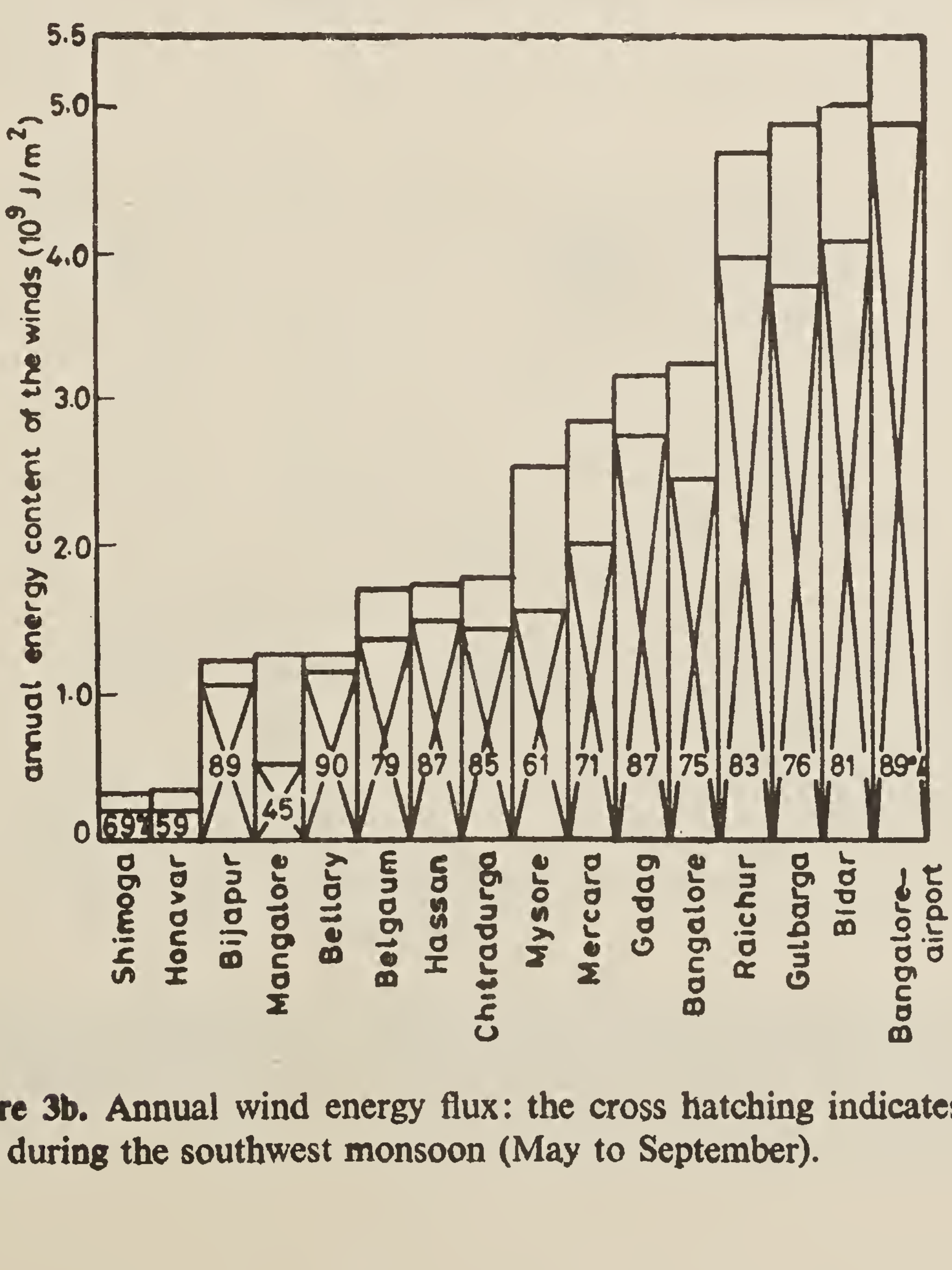

Figure 3b. Annual wind energy flux: the cross hatching indicates the portion available during the southwest monsoon (May to September).

Experiments using a wire gauze in a wind tunnel (Pelser 1975) suggest that an area density of 0·17% corresponds to a power loss of 10 to 15%.

From the studies of Musgrove (1976), Coty and Dubey (1976), Ljungstrom (1977), and Railly (1977), Ryle (1977) concludes that 'the vertical mixing of air allows one to site wind turbines so that their swept area corresponds to between 0·15 to 1·5% of the ground area'. He uses a value of 0·4% for the United Kingdom. This value will also be used in this report to get an estimate of the total power that could be generated in the State. It is hardly necessary to point out that since the prevailing wind speeds in most of Karnataka are low, windmill densities are never likely to reach values which would seriously affect any atmospheric phenomena or the weather.

Karnataka has a land area of $1{\cdot}92\times10^5$ km^2; of this, the 18·4% that is forested will be assumed to be unavailable for installation of windmills.

2.5. *Energy extraction*

2.5a. *Achievable windmill efficiency* The ratio of the power P that a windmill rotor can extract to the power available in the wind is known as the power coefficient of the rotor,

$$C_P = P/\tfrac{1}{2}\rho A V^3,$$

where A is the swept area of the rotor. It was shown by Betz that even an ideal actuator disc cannot have a C_P greater than $16/27=0{\cdot}592$.

In fact, even this limit is never reached in practice. The power coefficient of any windmill depends on the tip speed ratio $\lambda=\pi nD/V$, where D is the rotor diameter and n the number of revolutions per second. The functional relationship between C_P and λ is characteristic of the rotor type. Simple rotors like the Savonius

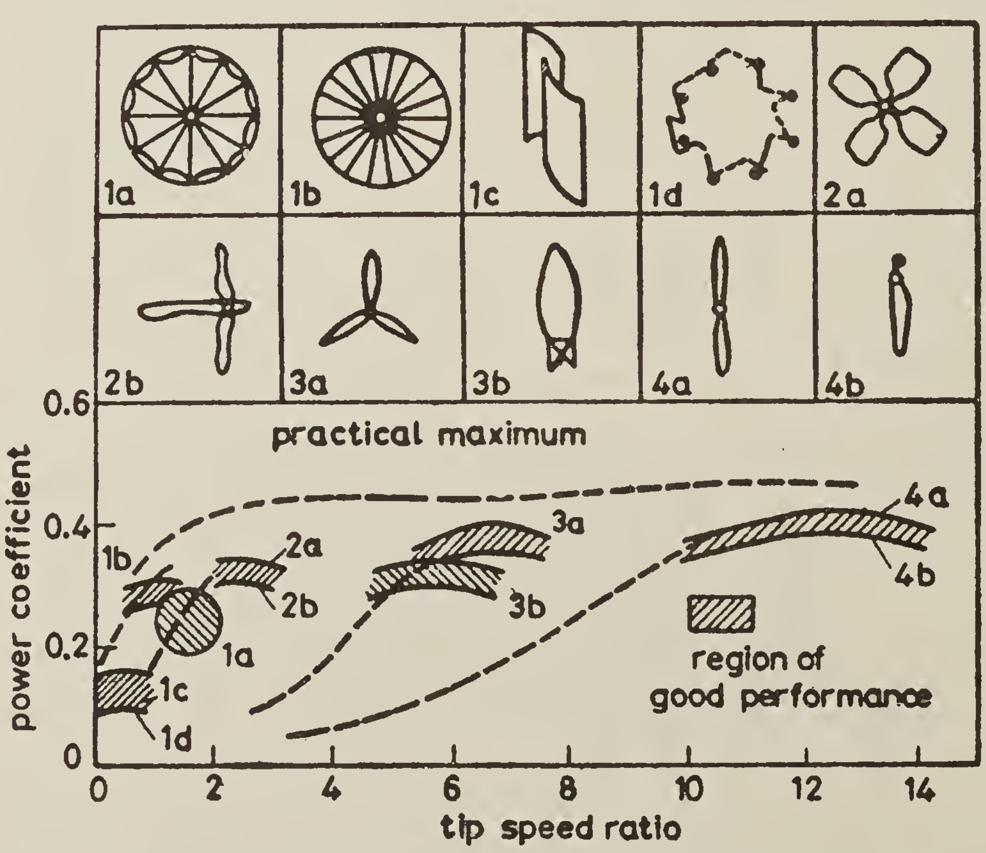

Figure 4. Various windmill rotors and their characteristics: **1a** Cretan sail type; **1b** American multivane; **1c** Savonius; **1d** Chinese sail type; **2a** cambered metal blade; **2b** Princeton sail wing; **3a** three-bladed propeller; **3b** Darrieus; **4a** two-bladed propeller; **4b** single bladed propeller. Source: ESCAP (?)

type produce $C_{P\ max}$ of upto 0·3 (Turnquist & Appl 1975); higher values, upto about 0·45, are associated with rotors using sophisticated aerofoil shapes. Figure 4 shows sketches of different rotor types and their characteristics (Anon, undated); more details will be found in Shrinivasa *et al* (1979a).

2.5b. *Effect of cut-in and unfurling speeds* As stated already, wind speeds could show strong fluctuations; but the full range cannot be used for turning windmills. Typically, a windmill starts working at a wind speed called the cut-in speed below which hardly any work output is delivered. On the other hand, windmills are usually designed such that, for reasons of safety, they do not operate above a certain 'unfurling speed'. Hence only the energy content of the wind *between* these two speeds will be of interest for windmill applications. To estimate this, one would require the speed-duration curve for each region. However, continuous (or even hour-by-hour) records of wind speeds are kept at only three stations in Karnataka; the rest have at best daily averages.

As an example of the effect of these limiting speeds, consider the small wind electric generator KSV-800 rated at 0·85 kW, manufactured by Electro GMBH, Switzerland (DST 1973), which could be conveniently used in Bangalore. It has the following parameters:

cut-in speed	= 4 km/hr (1·1 m/s),
rated speed	= 32 km/hr (8·9 m/s),
unfurling speed (estimated*)	= 35 km/hr (9·7 m/s).

Yearly loss in energy due to these limits in the operating speed would be 15%, as estimated from the wind data for Bangalore Airport.

2.5c. *Loss due to load mismatching* As figure 4 shows, C_P generally falls off rapidly from its maximum value with any change in tip-speed ratio. To obtain the maximum possible net output from the windmill at any given wind speed, the torque absorbed by the load should match the torque developed by the rotor at $C_{P\ max}$ and hence the power absorbed by the load should vary as V^3. Also for operation at $C_{P\ max}$, the corresponding tip speed ratio remains constant, hence the rev/min of the load should vary as V. Therefore, the torque absorbed by the load should vary as V^2 or equivalently as the square of the rev/min. Failure to achieve this load torque variation can reduce the useful output from the windpump considerably, as is evident from the sample calculations presented in figure 5a. Some wind electric generators have provision to modify the torque demand when the winds are high (der Kinderen & van Meel 1973). However, small inexpensive windmills (like the American water pumping windmills, Savonius rotors or Cretan type windmills built with sails) generally carry only a simple load (like a pump or a grinding wheel) without any controls. Their overall efficiency† falls rapidly as the wind speed in-

*The precise value of the unfurling speed for the KSV-800 is not known, but the value quoted is typical for machines of this kind. If the unfurling speed were 40 km/hr (11.1 m/s), yearly loss in energy would go down to 7%.

†Overall efficiency=(useful work delivered by the utility system)/(energy available in the wind).

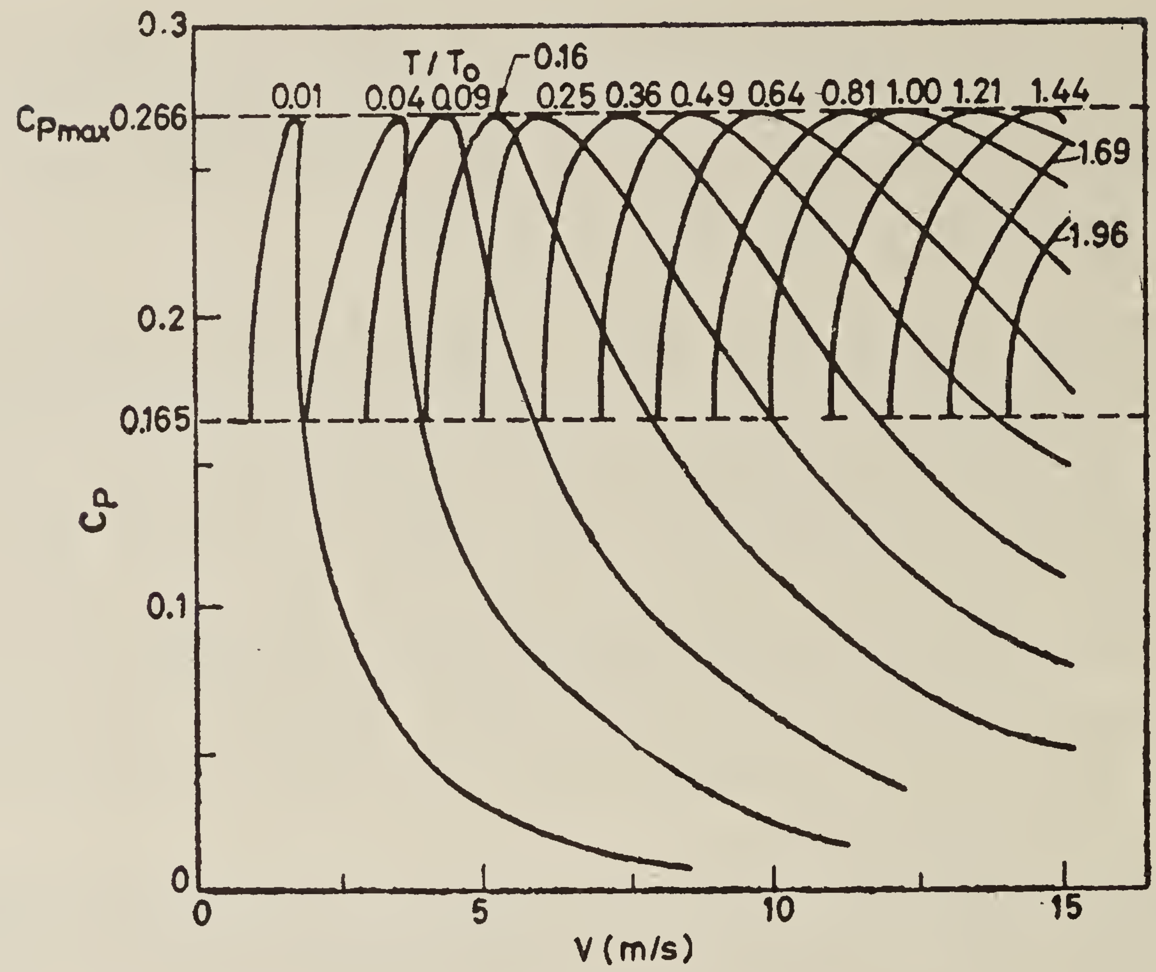

Figure 5a. Performance of an assumed rotor (whose characteristic is given in figure 5b): T_t Torque applied on the rotor. T_{0t} =Torque required to start the rotor at 10 m/s wind; curves indicate constant torque lines. Dotted line corresponding to C_P=0·266 ($C_{P\,max}$) indicates rotor output with load-matching.

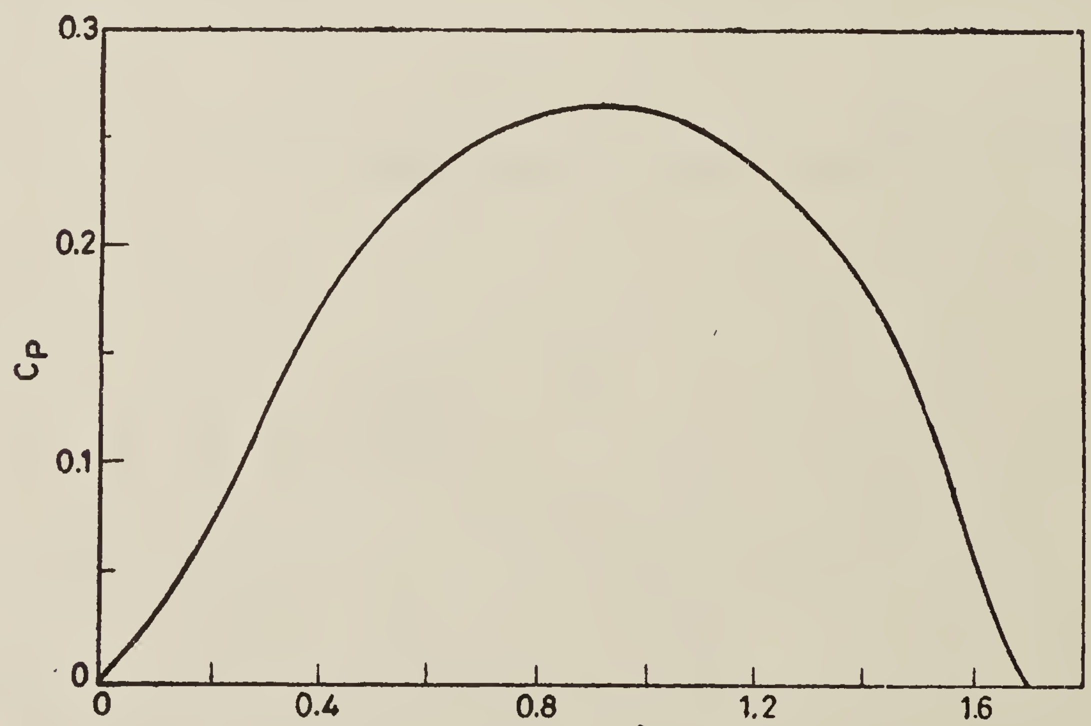

Figure 5b. Characteristics of an assumed rotor (Savonius type). Source: Newman (1974).

creases. However, it can be inferred from figure 5a that proper load matching will be able to increase the output of these windmills substantially.

The overall efficiency of a simple windmill when the winds are not steady is about 6–7% according to Golding (1962). The Indian Institute of Science windmill has 11% efficiency at the design speed but averages to less than 4% when varying wind speeds are encountered (Govinda Raju & Narasimha 1979a). We therefore believe that even simple windmills can in principle achieve overall operating efficiencies of about 15%, if provided with suitable load-matching devices (Shrinivasa *et al* 1979b).

However, inexpensive load-matching devices are yet to be built. Therefore, for estimating the potential of the State we will use a value of 10% as the economically feasible overall efficiency of extraction of energy from the wind.

2.5d. *Other losses* These include energies in high frequency wind fluctuations and hydraulic losses. The former are estimated to be of the order of 8% of the output of the rotor (Shrinivasa & Sastry 1978); the latter are assumed to be about 20% of the pump output.

2.5e. *Summary* Based on the above estimates, the energy flow in a typical 'simple' windpump (without load-matching) is illustrated in figure 6. It is seen that the final useful output is only about 4% of the energy content of the wind; even this figure is not always achieved!

It is clear from the figures quoted above that simple load-matching devices, if found feasible, could dramatically increase the output of windmills.

2.6 *Total extractable energy*

This is estimated on the basis of the following assumptions which have already been discussed in the earlier sections:

(i) Annual energy pattern factor = 5.5.

(ii) The overall efficiency of extraction of energy from the wind=10% (with suitable load-matching devices).

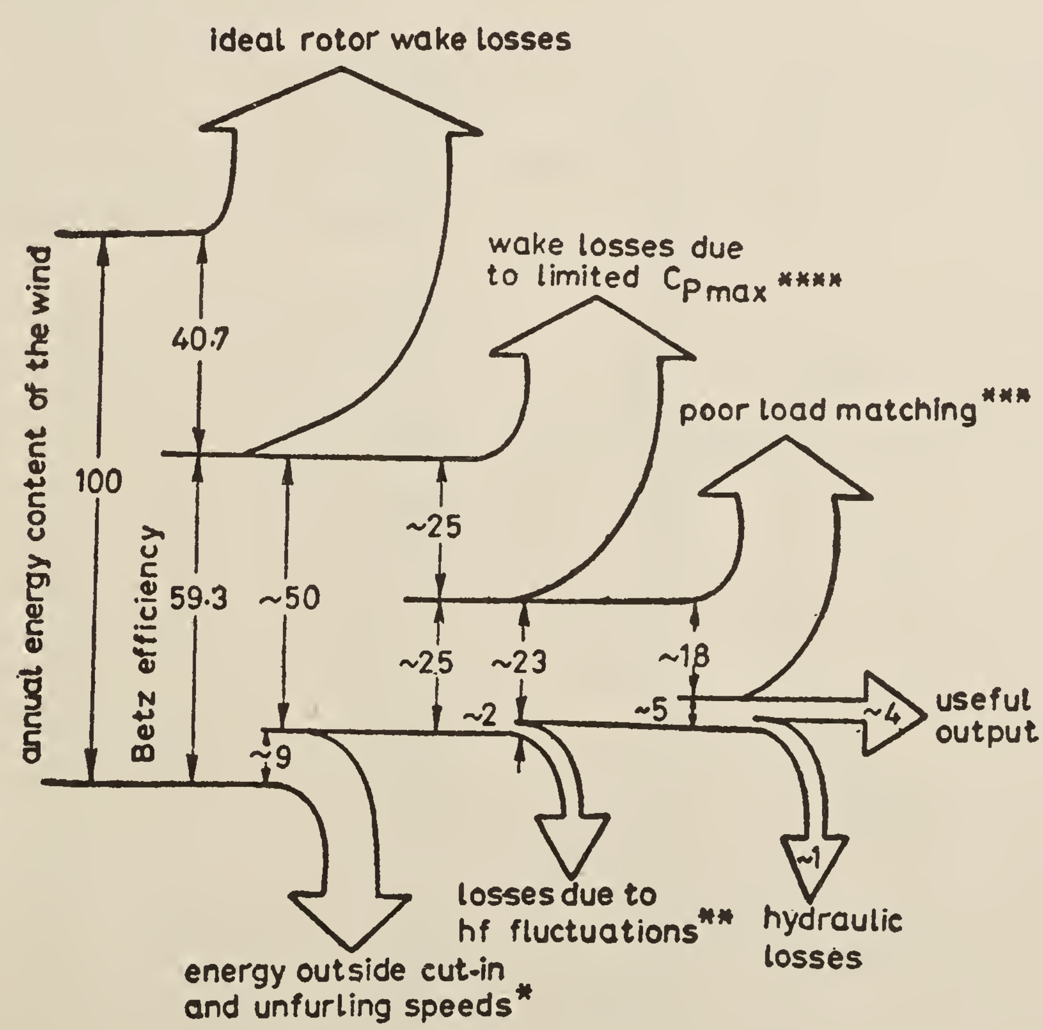

Figure 6. Energy flow in a typical simple windpump (the numbers in the figure are only rough indicators). *Energy outside 1·1 m/s and 9·7 m/s at Bangalore airport. **Losses estimated for a hypothetical wind pump. ***Losses estimated for a wind-pump rated at 4·2 m/s. ****Corresponds to an American multiblade type rotor.

(iii) The wind velocities measured at the meteorological stations are valid in the entire district in which each station is located. Where a district has no station at all, the mean wind speed is the same as in a neighbouring district in the same geographical region.
(iv) The windmill area that can be used for extraction of energy from the wind is 0·4% of the total unforested land area.

The energy estimates so derived are shown in table 3 where they are also compared with the low tension electrical energy consumption in the respective areas. It is seen that the total extractable wind energy in the State is about 40×10^9 kWh ($=1{\cdot}4 \times 10^{17}$ J) per year; this may be compared with the total electrical energy consumption in the State, of only about $3{\cdot}4 \times 10^9$ kWh ($0{\cdot}12 \times 10^{17}$ J) in 1972-73. Thus, even with the relatively low wind velocities prevailing in the State, the possibility of exploiting wind energy deserves serious consideration.

3. Technological problems

Two important factors that affect the economic viability of any product that is meant for use in rural areas are its first cost, and the ease and cost of maintenance. These factors have been discussed in relation to windmills by Govinda Raju & Narasimha

Table 3. Estimates of wind energy potential

District	Annually extractable energy 10^9 kWh	(10^{15} J)	Low tension electrical energy consumed 10^6 kWh	(10^{12} J)
1. Bangalore	3·4	(12·0)	290	(1000)
2. Belgaum	2.2	(7·9)	47	(170)
3. Bellary	1·1	(4·0)	31	(110)
4. Bidar	2·9	(10·0)	27	(97)
5. Bijapur	2·2	(7·9)	61	(220)
6. Chikmagalur	0·2	(0·7)	16	(58)
7. Chitradurga	1·3	(4·7)	51	(180)
8. Coorg	0·8	(2·9)	8	(29)
9. Dharwar	1·6	(5·8)	86	(310)
10. Gulbarga	8·6	(31·0)	29	(100)
11. Hassan	1·2	(4·3)	26	(94)
12. Kolar	3·6	(13·0)	84	(300)
13. Mandya	1·4	(5·0)	18	(65)
14. Mysore	2·4	(8·6)	94	(340)
15. N. Kanara	0·06	(0·2)	14	(50)
16. Raichur	7·0	(2·5)	26	(94)
17. Shimoga	0·2	(0·7)	39	(140)
18. S. Kanara	0·5	(1·8)	42	(150)
19. Tumkur	4·8	(17·3)	73	(260)
Total	40	(140)		

Total electricity consumption in 1972-73: $3{\cdot}4 \times 10^9$ kWh (12×10^{15} J) (Source: Sen Gupta 1977)

1979b); they have pointed out and illustrated how a 'soft' design, involving local materials, skills and labour, can keep costs down by utilising technologies available in or accessible to rural areas.

Apart from these general considerations, there are certain specific technological problems that demand attention, and these are discussed below.

3.1. *Non-availability of suitable pumps*

It has been argued in § 2.5c that, when the wind speeds fluctuate, the torque absorbed by the pump should vary as the square of the rotor angular speed to enable the rotor to extract energy from the wind at maximum efficiency. However, a pump with this characteristic that delivers water at a reasonably high efficiency does not seem to exist as of today. The two major pump-types available suffer from the following difficulties.

(i) In the absence of frictional losses, a positive displacement pump has the undesirable characteristic that it absorbs a nearly constant torque at all speeds. However, as the stroke rate increases the torque absorbed also increases rapidly due to mounting hydraulic losses, and this helps the rotor to operate closer to the design C_p. Nevertheless the windpump output still remains poor (as is shown by the sample calculation presented in figure 7), because the portion of the torque used to overcome hydraulic losses does not contribute to the pump output, but only increases the inefficiency of pumping.

(ii) Centrifugal pumps have nearly quadratic torque absorption characteristics with respect to their angular speed. However, their pumping efficiencies decrease rapidly as one operates them away from the design rpm (figure 8). Hence these pump-types are also unsuitable.

Therefore one cannot help concluding that the non-availability of pumps suitable for coupling with windmills is a major hurdle in improving the output of windpumps. The problem is particularly severe where wind speeds are not high, as one cannot afford to spill any energy.

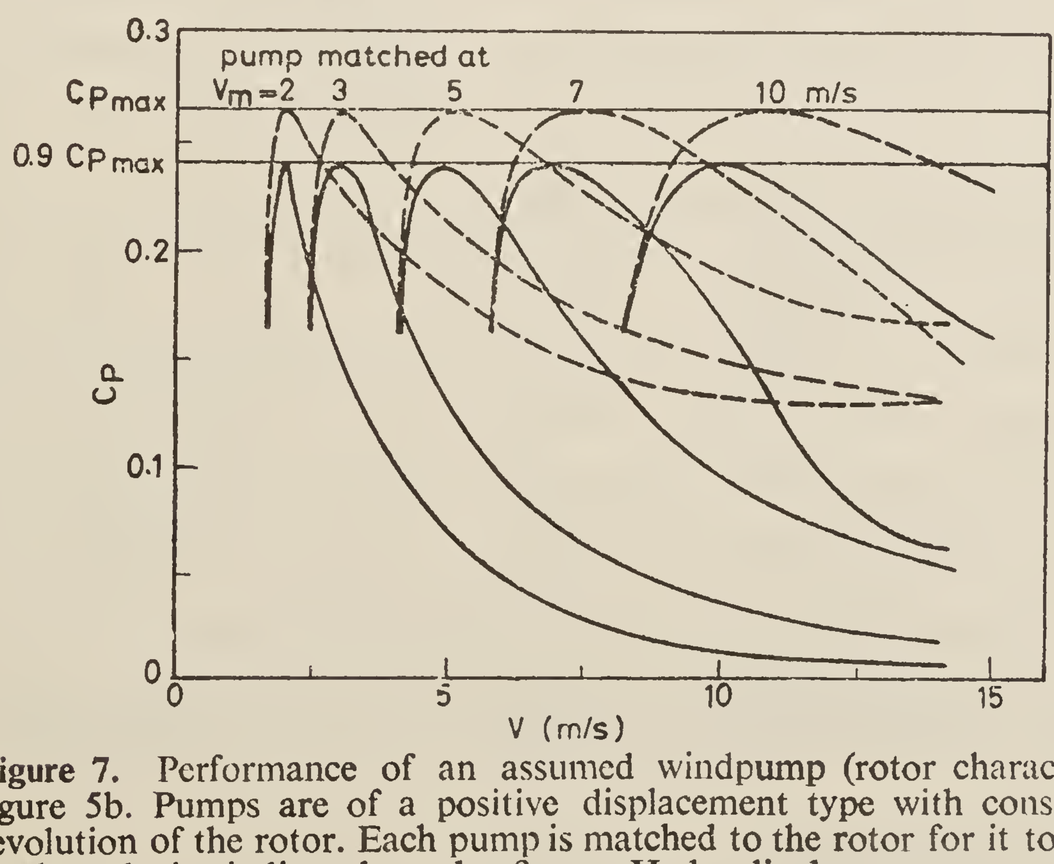

Figure 7. Performance of an assumed windpump (rotor characteristic is given in figure 5b. Pumps are of a positive displacement type with constant discharge per revolution of the rotor. Each pump is matched to the rotor for it to operate at $C_{P\,max}$ at the velocity indicated on the figure. Hydraulic losses are assumed to be 10% at the match point.); dotted lines indicate rotor output and the full lines pump output.

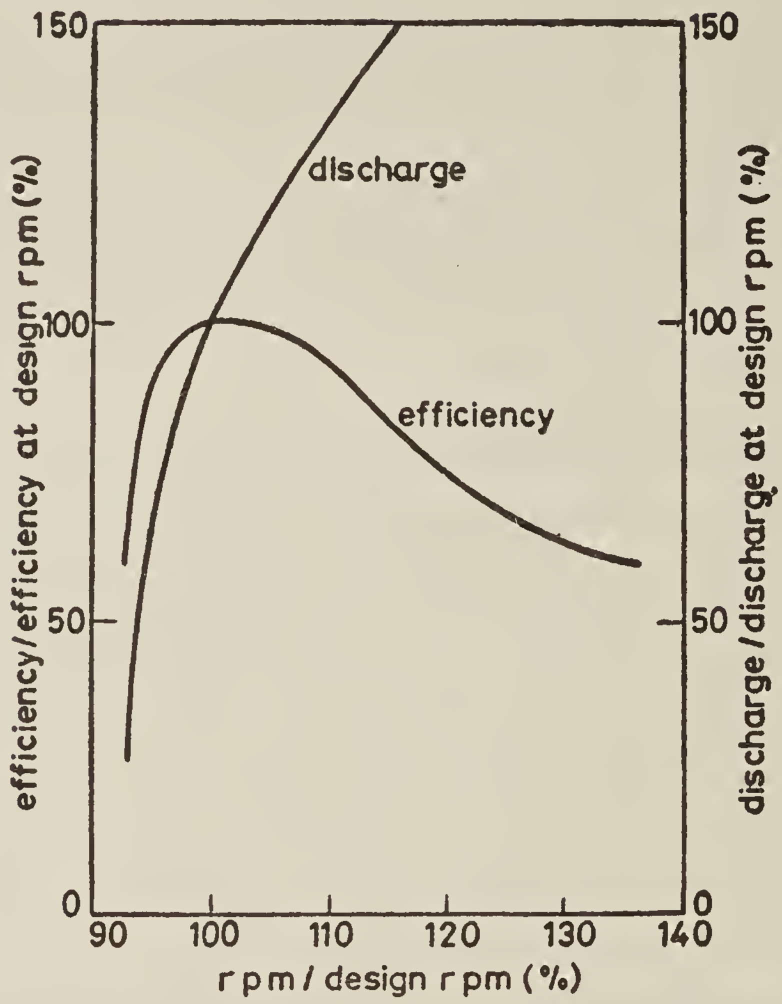

Figure 8. Variation of the overall efficiency of a typical centrifugal pump with its rpm. (Source: Lazarkiewicz & Troskolanski 1965).

Some developmental work is in progress at the Indian Institute of Science (Rajagopalan & Govinda Raju 1979) to design and fabricate a positive displacement pump whose stroke can be programmed to vary suitably with the rotor angular speed. A windmill with a similar pump has also been attempted at Auroville, Tamil Nadu (see Jaap *et al* NAL in 1979).

3.2 *High cost of wind pump towers*

According to Merriam (1972), the cost of an all-steel tower is 50% more than the cost of the rotor and gearing for traditional multivane water pumpers. Standard four-post towers of 21 to 47 ft (6·7 to 14·3 m) height, supplied by Aermotor, USA for rotors of 6 to 16 ft (1·8 to 4·9 m) diameter, cost from US $ 535 to 3175, whereas the rotors themselves cost between US $ 465 and US $ 4235 (NAS 1976). Thus it appears that the tower accounts for a major share of the total cost of the wind pump itself (anywhere between 40 to 80%). The situation is further aggravated in Karnataka because of the high variability of the winds: even though the annual mean wind speed may be rather low, one does occasionally get very high winds. For example, according to Tewari *et al* (1979), during a three-year period gust speeds in Bangalore exceeded 20 m/s nine times and 25 m/s once, while the annual mean speed was less than 4 m/s. Hence, towers for a given windpump output are often required to withstand disproportionately larger loads than what they normally experience.

It is therefore important to look for inexpensive tower designs. Among the technological options available to reduce the load on the tower during high winds are:

(i) feathering of the blades,
(ii) turning the rotor away from the wind,

(iii) partially furling the sails,
(iv) introducing certain elements on the rotor which will unfurl the sails at predetermined windspeeds in such a way that the rotor drag is reduced.

However, it appears that enough experience is not yet available to enable designers to confidently select towers which can be designed for only relatively low wind speeds.

3.3 *Lack of multiple utility load systems*

It has been observed by Merriam (1972) that multipurpose utility load is the best way to put a windmill to maximum use. As nearly 80% of the annual energy content in the winds in Karnataka is available during the southwest monsoon (figure 3b) when the need for pumping may not always be severe, it stands to reason that alternative uses for the rotor output must be identified to derive larger benefits from the investment on windpumps.

4. Economics of windpumps

Table 4 gives the approximate costs and the quantity of water lifted by pumps driven by diesel, electricity and wind. Tewari (1978a) has compared these alternatives on the basis of discounted cash flow (i.e. the amount of cash one should have now to take care of the capital and running costs over the life of the system). However even a favourable comparison on the basis of discounted cash flow is not sufficient to justify adoption of one of the alternatives; it is necessary to consider the return from the land. We therefore briefly examine various scenarios relevant to the windie rregions of the State.

The following facts have to be considered before the economic viability of windmills can be assessed.

(i) The districts in the northern maidan where winds are appreciable happen to be in the semi-arid tropics (with a rainfall of 500 to 1000 mm per year).

(ii) Parts of the region enjoy supply of irrigation water from canals, reservoirs or tanks; here pumping requirements are not severe, and may well be adequately met with bullock- or even man-power.

Table 4. Capacity and cost of some typical electric, diesel and wind pumps

Description	Cost Rs	Discharge	Source
3·5 hp (2·2 kW) electric motor with pump, plumbing and pump house	3,000	24,000 litres/hr	Tewari (1978b)
3·5 hp (2·6 kW) diesel engine with pump, plumbing and pump house	4,500	24,000 litres/hr	Tewari (1978b)
Sherman's Madurai windmill	5,480	6000 litres/hr in 16 km/hr wind	Sherman (1975) in Tewari (1978b)
NAL sail type	10,000	6000 litres/hr in 10 km/hr wind	Anon 1979
Smith's Sholapur windmill	14,000	6,500 litres/hr in 16·7 km/hr wind	Smith 1977 (private communication)
IISc windpump	3,000	1000 litres/hr in 12 km/hr wind	Govinda Raju & Narasimha (1979)

(iii) In the rest of the region, the chief crops grown are generally rainfed; either kharif (during the monsoon season), or rabi (using the moisture absorbed by the soil during the rains), or sometimes both, depending on the intensity and distribution of the monsoon rainfall in the particular year.

(iv) The monsoon season here is often plagued by mid-monsoon droughts, which could sometimes last over 40 days (as was the case in 1979). Ramana Rao & Havanagi (1979) have observed, on the basis of rainfall analysis, that areas like Gulbarga district are subject to moisture stress severe enough to spoil the crops in two out of five years. There is therefore a strong need for supplemental and life-saving irrigation, to protect the crops from such stress at least during the critical periods of their growth.

(v) Probably because of this same need, there are a large number of wells in the area. However the water yields from these wells are relatively low, because of unfavourable geological factors. The weathered rock that may contain water is a layer of only 10 m depth; except in some special locations where the hard granite below has fissures or joints, no advantage is obtained by digging deeper than 10 m. The yield of a majority of the wells (due to ground water percolation) is of the order of 1800 litres/hr, which is too meagre for pumping for irrigation. Therefore large-scale well irrigation may not be generally feasible in this region.

A large portion of the crops sown in these areas does not even get supplemental irrigation. However, the total agricultural output of the area is considerable, and the possibility of irrigation is therefore important from the point of view of annual food production.

(vi) Because of the uncertainties of the return from rainfed agriculture, the farmer is unable to risk his meagre capital to buy better seeds and fertilisers. As a consequence the yield per unit area in this region is very low. Experiments conducted over a period of three years at ICRISAT (Ryan *et al* 1979) have indicated that the yield from the land can be increased by about 3 to 5 times in such areas by using better seeds, better fertilisers and improved land and crop management practices. To tide over likely mid-monsoon droughts they recommend (for water sheds of at least 10–15 ha) that surface run-off be collected in a pond and used for life-saving and supplemental irrigation. However, the water needs to be applied only once or twice during the crop-growing period, and therefore could probably be satisfactorily lifted with bullock- or man-power.

To see where windpumps may be suitable, we must distinguish between pumping from surface sources like ponds, tanks, canals and reservoirs, and pumping from wells for supplemental irrigation.

In the former case the quantity of water pumped is generally large. The crop duty for even dry crops is of the order of about 500 to 600 mm per crop. The pumps normally operated handle about 25,000 litres/hr from depths of upto 15 m if necessary, as in the case of a 3 hp electric motor. Presently existing windmills in India can pump barely about 6,000 litres/hr in the non-monsoon winds of about 10 km/hr hourly average.

Where water has to be lifted only against small heads (of 1 or 2 m), traditionally either man- or bullock-powered pumps have been found adequate (see table 5), giving a discharge of about 10,000 litres/hr or more.

It must be noted here that, apart from the total water requirement for a crop (table 6), the *rate* of discharge is also an important factor, at least for crops other

Table 5. Outputs of traditional water lifts

Device	Source of power	Optimum lift (m)	Average discharge 10^3 litres/hr
1. Counter poise lift	Single man	1·2 to 4	8 to 11
2. Swing basket	Two men	0·9 to 1·2	14 to 19
3. Archemedian screw	Single man	0·5 to 1·2	14 to 19
4. *Don*	Single man	0·5 to 1	9 to 13
5. Water wheel	A pair of bullocks	1 to 1·2	40 to 60
6. Persian wheel	A pair of bullocks	5 to 10	14 to 18
7. Chain pump	A pair of bullocks	3 to 6	15 to 20
8. Self emptying rope and bucket lift	A pair of bullocks	4 to 6	10 to 15
9. Rope and bucket lift	Two pairs of bullocks	10 to 30	6 to 10

Source: Dakshinamurti *et al* (1973)

Table 6. Water requirements of field crops (other than rice*) at 70% field irrigation efficiency (in hot and semi arid tropics)

Seasons	Water requirement (mm)
Kharif (July–October)	600 to 700
Rabi (November–March)	600 to 700
Hot weather (March–June)	900 to 1000

*Water requirement of rice is 12 mm/day on clayed soils and 18 mm/day on loamy soils.
Source (Dakshinamurti *et al* 1973)

than paddy. This is because at low rates of discharge the percolation is too large to distribute water through field canals. Other means of distribution like sprinkler or drip irrigation require large capital investments and therefore are not in widespread use in India. From table 5 it can be seen that even the traditional water lifting devices give a yield of about 10,000 litres/hr. Therefore we assume for this report that either the windmills must provide this discharge rate or must be accompanied by small tanks of about 10 m^2 area and of 20,000 litres capacity, found adequate in the US to regulate the flow of water to the fields.

From experience in India, rotors of upto about 10 m diameter can be conveniently built even using local materials in the villages (see various reports in NAL 1979). To be useful, one must require that they pump a reasonable quantity of water from these windpumps even in non-monsoon winds. The data discussed in § 2.2 indicate that wind speeds with a monthly average of about 10 km/hr (2·8 m/s) are prevalent in the windier parts of Karnataka during the non-monsoon months. Tewari (1978a) observes that in Bangalore, hourly average wind speeds of about 10 km/hr (2·8 m/s) are usually found on the average for about 10 hr a day throughout the year. Using an hourly EPF = 2, the windpump under consideration can deliver about 2 kWh ($7{\cdot}2\times10^6$ J) per day in Bangalore assuming an overall efficiency of about 10% (with load-matching) and a pump mechanical efficiency of about 80%. This output is equivalent to about 8 hr from a pair of bullocks, and looks attractive.

However, without load-matching the output will fall to about a third, which cannot justify the investment on windpumps, particularly where the wind speeds are not very good. Windpumps without load-matching will therefore not be considered here.

An output of 2 kWh is equivalent to 70,000 litres of water lifted over a height of 10 m under the assumed efficiency of pumping. However at the lower pumping heads it may not be possible to maintain the assumed efficiencies. As an example we present the computed performance of the IISc windmill in figures 9a and 9b. Here as the wind energy flux increases 8 times (V changes from 20 km/hr to 40 km/hr) the pump output just about doubles. Even when the hydraulic loss coefficient (hydraulic loss/reference dynamic head) is reduced from 40 to 2·8, the output is only doubled (figure 9b). Therefore when one considers large discharges it will also become necessary to account for this increased hydraulic loss.

Hence it appears that outputs far in excess of 10,000 litres/hr are unlikely to be obtained during the non-monsoon months from a 10 m diameter rotor windmill which does not use a specially designed pump. (The largest output from wind pumps manufactured by Aermotor, a US windpump manufacturer, is about 13,000 litres/hr (NAS 1976).) Therefore we assume here that the output from simple windpumps would at best be about 20,000 litres/hr.

Based on the foregoing discussion, a variety of illustrative scenarios, both favourable and adverse, have been presented in table 7. The assumptions underlying these scenarios are the following.

(i) Crops like sorghum, bajra, maize and wheat require about 500 mm of water (after taking into account a field irrigation efficiency of 70%), and paddy requires 1,500 mm per crop (see table 7).

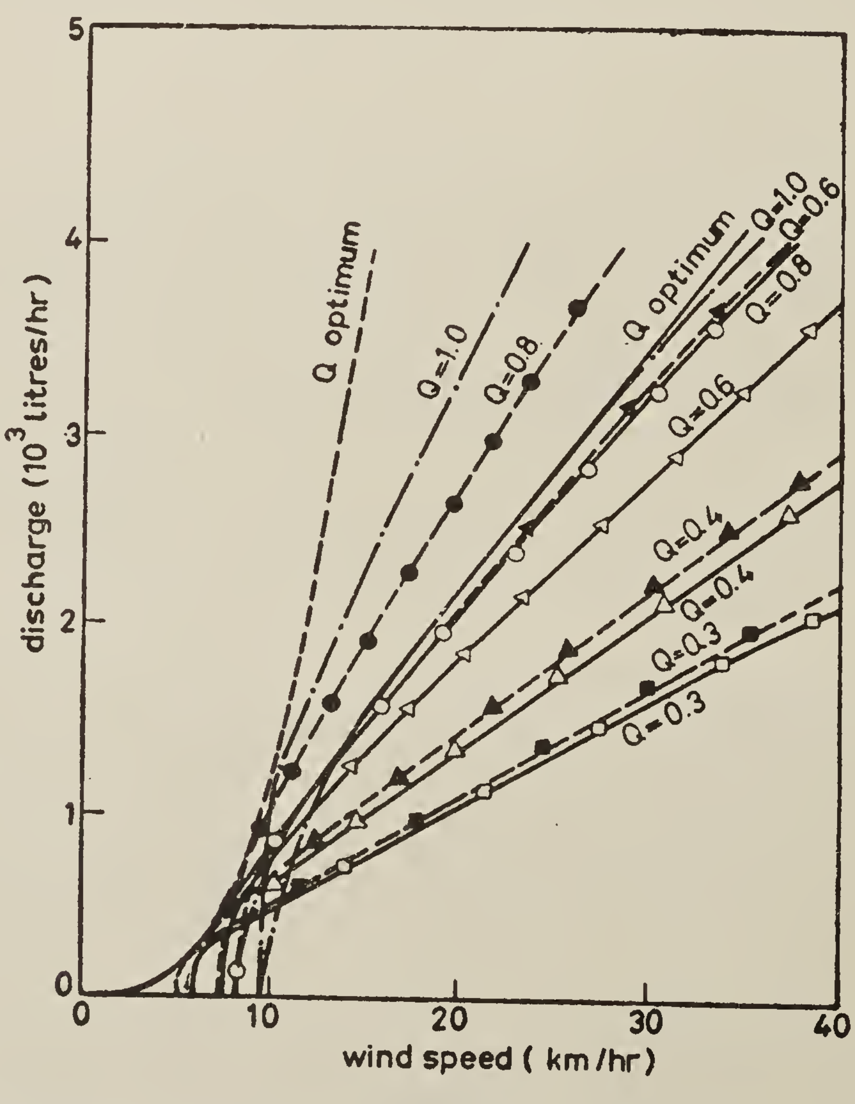

Figure 9a. Performance of IISc wind pump. Net head is 5m. Q is the pump displacement in litres/stroke. Full lines indicate performance with hydraulic loss and the dotted lines without any loss (k=hydraulic loss/reference dynamic head=46). (Source: Rajagopalan & Govinda Raju 1979.)

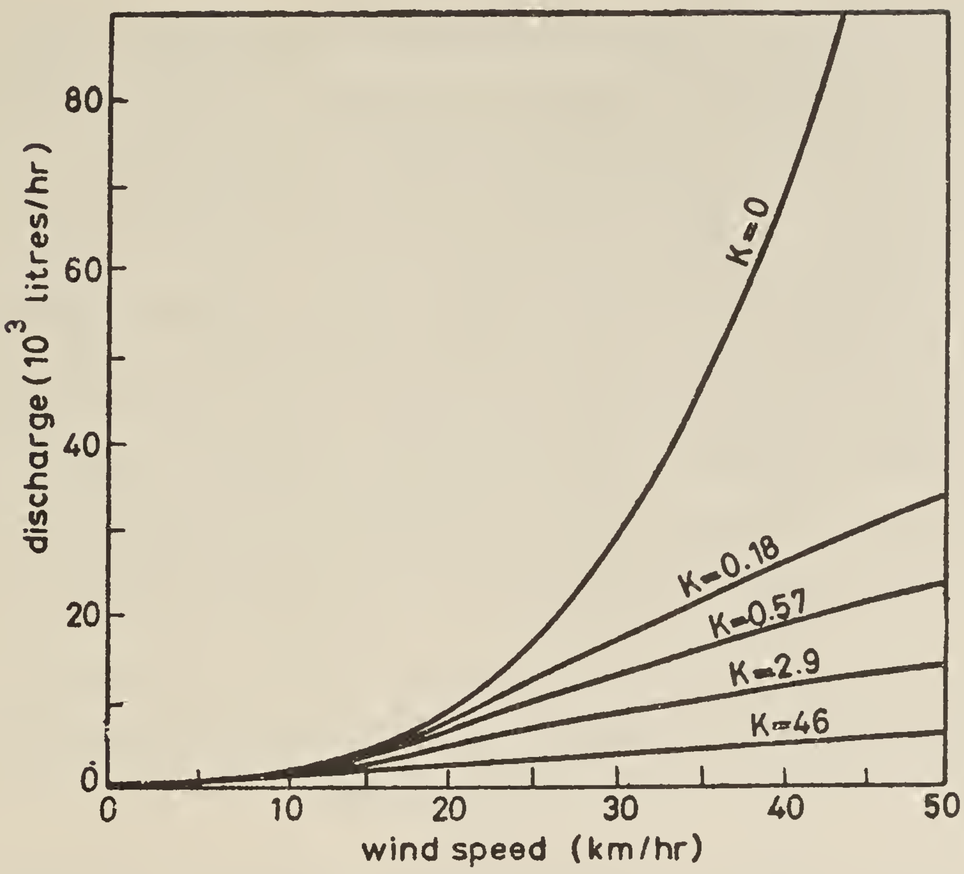

Figure 9b. Performance of IISc windpump with load matching. Different size pipes and suitable pumps are to be used to achieve the hydraulic loss coefficients indicated on the figure. In each case the pump stroke is programmed so that the rotor can operate at $C_{P\,max}$. (Source: Rajagopalan & Govinda Raju 1979.)

Table 7. Economics of windpumps

Sl. No.	Land area ha	Crop	No. of crops	Yield/ha kg (for each crop)	Wind pump cost (Rs.)	Tank cost	Depreciation %	Repair and maintenance %	Annual return %
Well water									
1.	0·5	Rice	2	5,000	12,000	No tank	10	5	18
2.	0·5	Rice	2	2,500	12,000	No tank	10	5	-ve
3.	0·5	Rice	3	5,000	12,000	No tank	10	5	33
4.	0·5	Rice	2	5,000	5,000	No tank	20	10	45
5.	0·5	Rice	3	5000	5,000	No tank	20	10	81
6.	0·5	Rice	3	2500	5,000	No tank	20	10	14
7.	0·5	Rice	2	2500	5,000	No tank	20	10	0
8.	0·5	Rice	3	5000	12,000	No tank	3·3	0	44·8
9.	1·5	Dry crop	2	5000	5,000	1,500	20	10	130
10.	1·5	Dry crop	2	2500	5,000	1,500	20	10	35
11.	1·5	Dry crop	2	2500	12,000	1,500	10	5	17
12.	1·5	Dry crop	2	5000	12,000	1,500	20	10	68
Water from a large source									
13.	3	Dry crop	2	5000	5,000	No tank	20	10	280
14.	3	Dry crop	2	5000	12,000	No tank	10	5	150
15.	3	Dry crop	2	2500	12,000	No tank	10	5	50
16.	3	Dry crop	2	2500	5,000	No tank	20	10	94

(ii) The possible yield for each crop, under favourable conditions, is about 5,000 kg/ha (Dastane *et al* 1970). However the average yield of paddy in India according to Dakshinamurthy *et al* (1973) is only 1,000 kg/ha. The projected average paddy

yield for Karnataka in the year 2000 AD is 2,400 kg/ha (Iyer 1975). We shall consider here a yield of 2,500 kg/ha as the lower bound under favourable conditions.

(iii) The crops can be sold at a uniform price of Re. 1/kg.

(iv) The variable cost of each crop (including expenditure on fertilisers, seeds etc., but not on labour) is Rs 1,000 per hectare.

(v) A well can yield 60,000 litres of water per day uniformly throughout the year. The larger source of water (e.g. a tank) considered here can yield 200,000 litres/day.

(vi) Two windpumps, both with a rotor diameter of 10 m, will be considered. One of these, with a life of 10 years, is assumed to cost Rs 12,000 (10% depreciation per year), and the other (5-year life) Rs 5,000 (20% depreciation per year). The maintenance and repair charges are taken to be 5% and 10% per year of their respective first costs.

(vii) When the average discharge from the windpump is less than 10,000 litres/hr, a tank of 20,000 litres capacity just above ground level is considered necessary. Such a tank is assumed to cost about Rs 1,500, and require 10% of this cost for annual maintenance.

One can draw several useful conclusions from the results displayed in table 6. Obtaining a reasonable return on a half-hectare rice field is clearly very difficult: 3 crops per year each with a high yield of 5,000 kg/ha, and a wind pump costing only Rs 5,000, are required to give a return of more than 50% on the investment. On the other hand, with two dry crops per year on a 3 ha farm, either a relatively high yield of 5,000 kg/ha, or a windmill that costs less than Rs 5,000, promises an appreciable return.

It is clear from these figures that only an integrated programme that includes the development of suitable windmills on the one hand, and of appropriate water- and crop-management practices on the other, promises any success. Certainly such a programme is worth pursuing, in view of the increasing costs of both water and energy for irrigation.

5. Conclusions

We have shown that the total wind energy potential of Karnataka State is about an order of magnitude higher than current electrical energy consumption in the State. Although the wind velocities are too low or variable over large parts of the State to enable economic exploitation, the data available, with all their limitations, indicate that there are certain districts in the northern maidan of the State (namely Gulbarga, Raichur, Bidar) where wind velocities are moderately good and where a serious experiment to exploit wind energy would be definitely worthwhile. However, for such an experiment to be successful it is important that the nature of possible applications should be constantly kept in mind. For example, if the application is irrigation, it is necessary that the programme should be integrated carefully with the needs of the crops grown in the particular region and the water resources there; and should indeed include within its scope possible improvements in land and water management practices.

A technological target for windmills that might find application in rural areas would be the design and construction of a windmill of about 10 m rotor diameter costing not more than about Rs 10,000, with suitable load-matching device and pump

that will provide an output of about 10,000 litres/hr in 10 km/hr hourly average winds. No windmill with these characteristics is available as of today, but it is our belief that the target set out above is technically feasible. A first cost of even Rs 10,000 may appear to be on the high side when compared to such alternatives as electrically or diesel-driven pumps, but this comparison is superficial and misleading as it takes no account of the hidden subsidy that supports these more familiar sources of energy (Reddy & Krishna Prasad 1977). The use of such windmills should be particularly attractive in the semi-arid tropics to provide supplementary irrigation for such dry crops as maize, jowar etc., especially where water is available at relatively low depths of the order of 10 m; in Karnataka State, it seems clear that in the districts of Raichur, Gulbarga and Bidar and possibly also Bangalore and the Western Ghats, more detailed wind surveys should be immediately carried out, accompanied or followed by a programme of erection of windmills of different designs to meet rural applications.

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Handpumps: problems and the search for remedies

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Abstract. This paper gives a brief survey of research and development work done on handpumps in India as well as elsewhere and sets out the approach adopted by the ASTRA Working Group. Ten ways in which a handpump breaks down in practice have been identified. The physical reasons behind each type of breakdown have been analysed. Remedial measures have been developed from this analysis. Laboratory test rigs fabricated to evaluate these measures have been described and some experimental results presented. The course of further work has been charted.

Keywords. Rural drinking water supply; handpumps; failure modes; design modifications; maintenance costs; reliability; cup washers; poppet valves; valve seals; straight line mechanism; diffusion of technology; information system; rural artisan training.

1. Introduction

The traditional sources of drinking water for Indian villages have been tanks, open wells and streams. Though villages must have been founded at locations where water was easily available, the water supply can change with time due, for example, to the lowering of the water table, the drying up of streams, the silting and breaching of tanks, or the progressive pollution of the water source. For many villages, therefore, the nearest current source of drinking water can be several kilometres away. For instance, as recently as 1972, about 11,000 villages (41 %) in Karnataka, involving a population of about 11 millions did not have easily accessible drinking water sources.

To remedy this serious situation, many governments felt that the simplest way of providing good drinking water all the year round was to drill borewells (to tap an aquifer) and to instal hand-operated reciprocating pumps in them. In Karnataka, for instance, 6375 successful borewells were drilled in 5305 villages between 1972 and 1976 and fitted with handpumps.

Very soon, however, handpump failure rates as high as 70 % at any given time were noticed. It was said that even new pumps did not last more than two months. Since the failure of a handpump (costing about Rs 1100) puts the borewell (costing about Rs 8000 on the average) out of use until the handpump is repaired, it became obvious that large expenditures, running into tens of millions, were being rendered infructuous, apart from affecting the water supply of millions of people.

The seriousness of the situation resulted in a number of international and voluntary agencies directing their attention to the problem. A variety of 'explanations' for handpump failures were popular—these ranged from slip-shod manufacture

and defective materials through villagers' negligence (and even vandalism) and poor maintenance to lack of popular involvement and the weaknesses of development-from-above.

It was in this context that ASTRA (the Centre for the Application of Science and Technology to Rural Areas at the Indian Institute of Science) was attracted to the problem. Its preliminary efforts, including the establishment of a borewell-handpump facility on the Institute campus, received a fillip when the Karnataka State Council for Science and Technology sponsored a project and constituted a Working Group which included senior officials from the Department of Public Health Engineering of the Government of Karnataka.

This paper is intended to record the progress of the project. It will describe the handpump, review the previous efforts to improve it, analyse the technical causes of failure, describe the modifications which have been incorporated and their impact and finally indicate future lines of work.

2. The handpump set

The handpump set consists of a pump-proper situated below the minimum level of ground water, an operating mechanism (the 'head') above the ground, a riser pipe to convey water to the surface and a connecting rod (the 'plunger rod') running inside it between the piston and the operating mechanism (figure 1). Although the principles of the pump are well known, brief descriptions of the components are given below, since (i) they form the background for the discussion on modes of failure and (ii) some of the terms are peculiar to handpumps.

2.1 *The pump*

The pump itself is a conventional reciprocating pump, consisting in its present form of a brass cylinder (figure 2) in which the piston moves. During the upward stroke of the piston, water is sucked from the well into the lower part of the cylinder and at the same time the water above is delivered at the ground level. The downward stroke just serves to return the piston to its original position. Two non-return valves of the poppet type, one in the piston (the 'upper valve') and the other at the bottom of the cylinder (the 'lower valve'), prevent the downward motion of water.

2.1a *The piston* The piston (figure 2) consists of a hollow body which is connected to the piston rod through the upper cage by screwed joints. The upper end of the body serves as the seat of a brass poppet moving inside the upper cage. Two leather cup washers, separated by a spacer, make up the piston packing. The upper cage is screwed onto the body till the cup washers are held firmly. The movement of water from one side of the piston to the other takes place through the hollow of the body.

2.1b *The lower valve* Like the upper valve in the piston (figure 2), the lower valve is also of the poppet type, the poppet being restrained by a cage. The lower valve poppet is lined on its bottom with a rubber seal to prevent water from leaking back into the well.

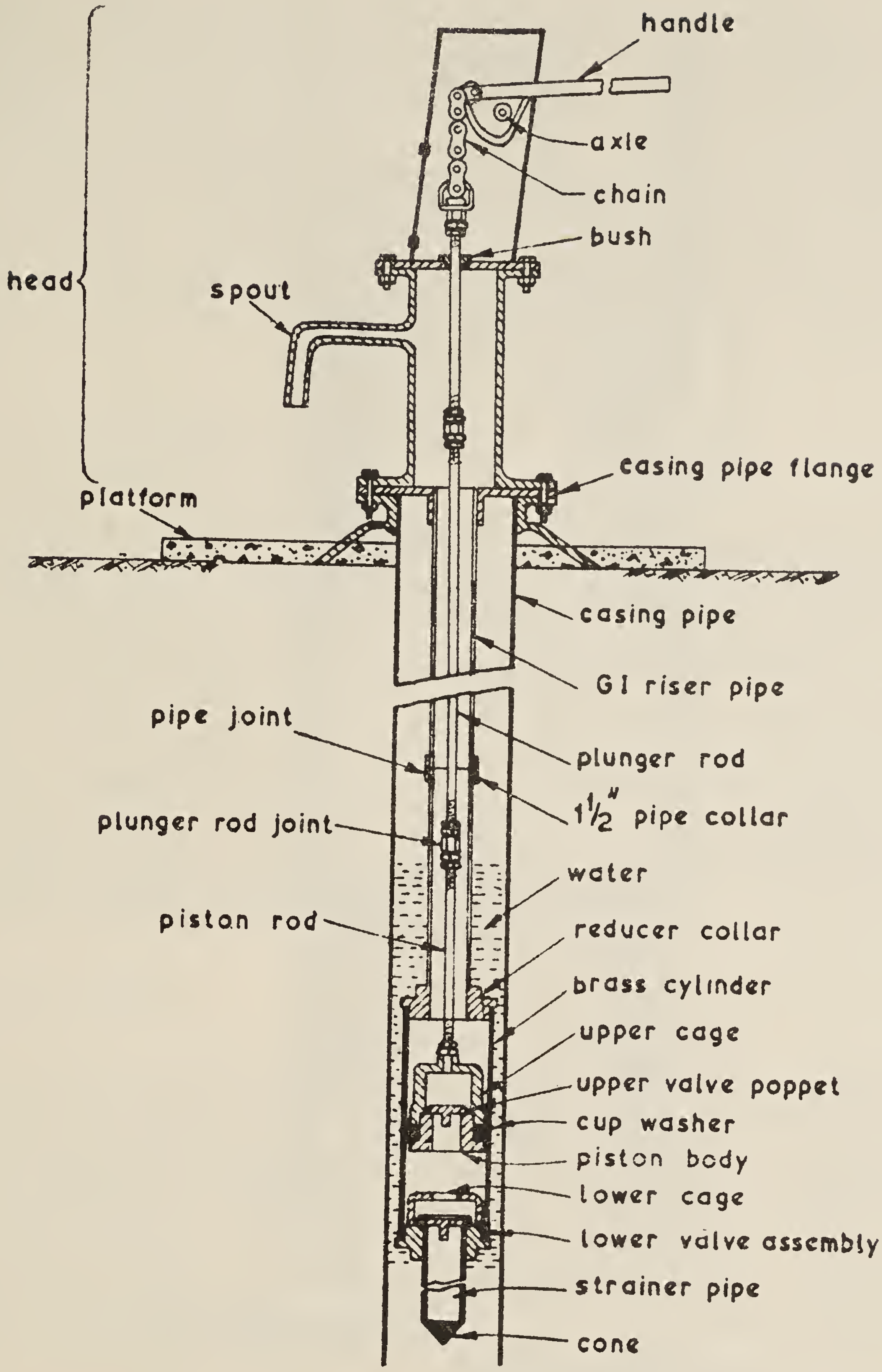

Figure 1. Section of handpump set.

2.1c *The plunger rod* Running between the piston rod and the surface, the plunger rod consists of galvanised steel rods 12 mm in diameter and about 3 m in length, joined to each other by threaded hexagonal nuts (figure 3).

2.1d *The riser pipe* The riser pipe consists of standard GI pipes of size 1½ (or 1¼ in some states) of about 6 m length, joined to each other by standard collars. Sometimes the pipes are cut to 3 m lengths for ease in handling, though the number of joints is doubled. The riser pipe is screwed into a collar welded to the bottom of the pump head near the ground level. The pipe therefore not only conveys water to the surface, but serves as a long suspension line for the pump as well.

2.1e *The head* The head (figure 1) is the part of the pumpset above the casing

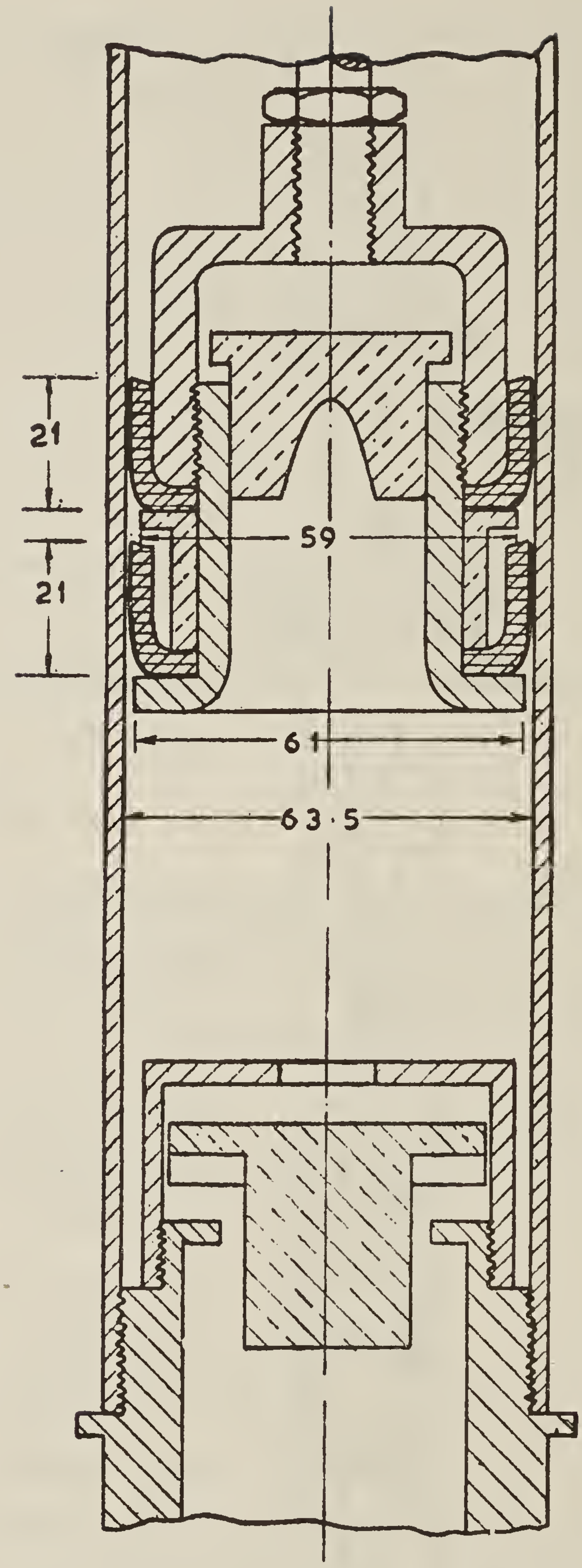

Figure 2. Section of pump proper.

Figure 3. Plunger rod joint.

pipe flange, to which it is bolted. The weight of the entire pumpset together with that of the water in it and the force applied while operating are thus transmitted to the casing pipe, and then through friction onto the ground. The top part of the head accommodates the operating handle which oscillates up and down about a fulcrum, as well as the mechanism which converts this rotary oscillation to linear reciprocating motion. The head has been the subject of a number of investigations, as a result of which it has undergone changes and in its current form in India (the Jalna head) uses a roller chain riding on a sector to achieve straight line motion (figure 4).

3. Brief review of handpump research

While a detailed consideration of the modes of handpump failure will be found later in the paper (§ 5), it will suffice at this point to say that the important trouble spots are the threaded connections in the plunger rod as well as the riser pipe, the leather cup washers, the upper and lower valves and finally the head; in other words, the trouble spots are distributed throughout the pumpset. Since handpumps are used all over the developing world and show high rates of failure everywhere, many research groups supported by national as well as international agencies have made efforts to improve them. The results of some of this work have been summarised in a publication brought out jointly by the UNEP and WHO (McJunkin 1977) which also contains an extensive bibliography on the subject.

3.1 *Some earlier studies*

A study financed by the USAID and conducted by the Batelle Memorial Institute concluded, *inter alia*, that (i) there was a lack of community spirit towards community water supply schemes and even vandalism, (ii) little maintenance attention was given to the pumps and (iii) the pumps had defects in the form of rough cylinders, generally too large piston packing, highly-stressed fulcrums and handles with poor alignment, too small bearing surfaces and poorly made valves and fasteners. Batelle developed new pumps for shallow wells as well as deep wells. However, the pumps do not appear to have been used in practice on a significant scale.

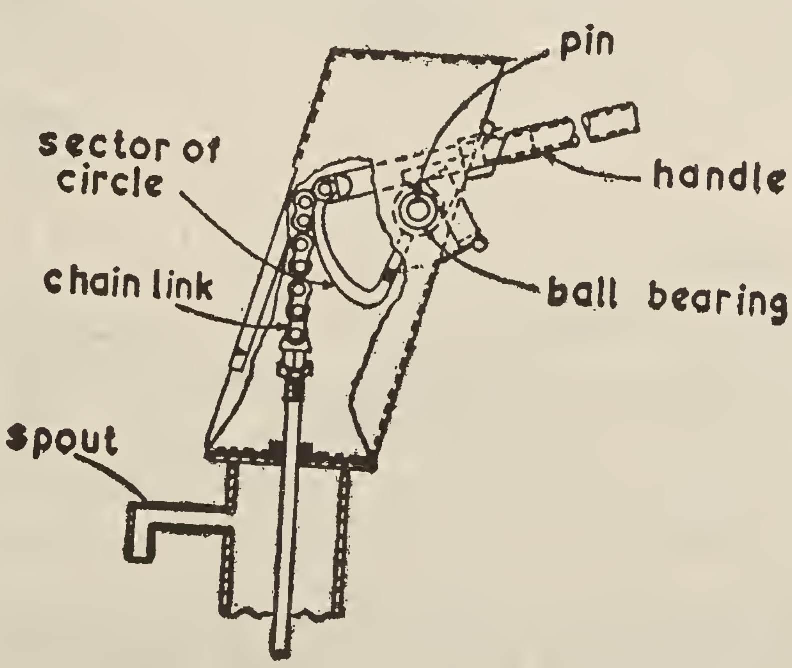

Figure 4. The Jalna head.

A study conducted by the All India Institute of Hygiene and Public Health supported by WHO and UNICEF showed that commercially available pumps needed to be repaired, on an average, once in 8 months. On the other hand, out of 15 pumps using components with better finish and stricter tolerances, only two needed repairs over a nine-month period. These are, however, contrary to field experience in many states in India.

3.2 *The Jalna head*

Conventional handpumps have had the conventional straight line motion mechanism: a well-known inversion (Phelan 1957) of the slider-crank mechanism (figures 5a and b). Figure 5c shows the form which this mechanism takes in practice. In order to avoid rapid wear of the bush through which the pump rod (an extension of the plunger rod) passes, two guide pillars and a cross-head are fitted. This was the head used in initial handpump installations in India, but it is difficult to manufacture satisfactorily in small workshops, and serious problems developed with the handle, the pins, guide pillars and the cross-head. This head is now superseded by the Jalna head (figure 4), developed by the Marathwada Sheti Sahayya Mandal of Jalna in the State of Maharashtra. In the Jalna head, some of the conventional rigid links are replaced with a flexible link in the form of a roller chain riding on a sector of a circle to which the axis of the connecting rod is a tangent, and whose centre is at the fulcrum of the handle. With the introduction of the Jalna head, components below the ground are likely to break down sooner than those above the ground; earlier it was the reverse. Though the Jalna head has its problems, it represents the most successful result of early handpump research.

3.3 *The Bangalore pump*

Another study was conducted on deepwell handpumps in India jointly by the Department of Minor Irrigation and Public Health Engineering of the Government of

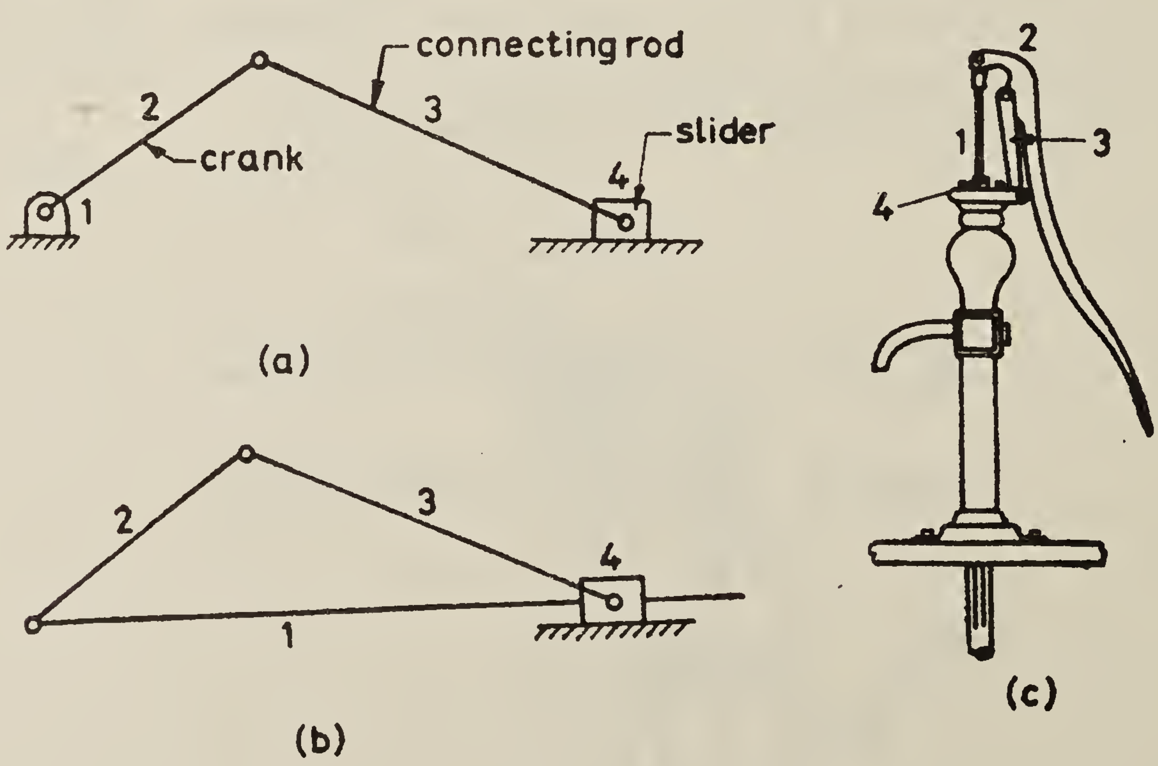

Figure 5. (a) Slider-crank mechanism (first inversion) (link 1 fixed)
(b) Slider-crank mechanism (fourth inversion) (slider 4 fixed)
(c) Actual form of (b) in handpumps.

Karnataka, the WHO and the UNICEF (Anon 1976). It concluded that all moving parts of pumps of several makes in the market were poorly matched, tolerances were too large and alignment was generally poor. A new pump was developed using, besides the Jalna head, nylon balls instead of metal poppets in the valves, neoprene cup washers as piston packing, a cylinder made of standard GI pipe lined with hylam (fabric impregnated with an epoxy resin), other valve and piston components made of rubber, nylon, neoprene, glass or hylam, sintered bearings instead of ball bearings in the head and finally a wire rope substituting the plunger rod. A prototype of this 'Bangalore pump' was tested for 1000 hr at 40 to 48 strokes per minute against an unstated head. It was found that the cylinder wear was less than 0·025 mm and the cup washers, after an initial wear of 0·6 to 0·9 mm showed no further wear over the final 534 hr of testing. However, this pump was never introduced in the market, apparently because of problems with the wire rope whose strands would untwist with time resulting in an increase in its length. It is said that the nylon balls (with metal cores to increase the effective specific gravity) when tried in the field went through the hole in the seating, and that the neoprene cup washers were also torn to pieces in a short time. However, tests in Bangladesh have shown (McJunkin 1977) that PVC cup washers last longer than leather washers in shallow wells.

3.4 *The India-Mark II pump*

This pump has also been developed in India, by the cooperative effort of the Government of Tamilnadu and the UNICEF. It has a Jalna head, modified so that it has a foundation independent of the casing pipe flange. A shaky casing pipe will not therefore transmit its vibration to the pumpset. Another new feature is that its cylinder is made of cast iron lined on the inside with a brass tube. It has now been installed for field trials in some states.

3.5 *The UST pump*

This pump, developed at the University of Science and Technology in Ghana (Blaho 1972), had a plastic pipe for conveying the water upwards, whose lower part served as the pump cylinder. The head did not incorporate any straight line motion mechanism, but the crank was directly joined to the plunger rod. This subjects the plunger rod to a lateral load and leads to rapid wear of the guide bush. It is also known from tests in Bangladesh (McJunkin 1977) that cylinders made of plastic material wear out quickly.

3.6 *Others*

The studies reported above deal with conventional piston pumps. Attempts have also been made to develop pumps that work on other principles. 'Oscillating liquid column pumps', in which the water column in the riser pipe is excited to vibrate at its natural frequency, drawing off water at the upper end during every rise in level, have been tested in Ethiopia as well as Bangalore (Gururaja 1976, Pandey 1979). They are apparently very sensitive to the operating frequency and their performance in wells more than 12 m deep is not known. The foot-operated 'Vergnet' pump developed in France (Anon undated) has a piston pump at ground

level forcing water into a flexible chamber inside a rigid cylinder located below the water level in the well. The expanding chamber pushes water up through a riser pipe, and when contracting during the next half of the cycle, sucks water into the cylinder. The 'Petro' pump (McJunkin 1977) developed in Sweden consists of a flexible cylinder anchored in the well below the water level and suspended from the riser pipe, which is moved up and down. The cylinder expands and contracts alternately, sucking water into it and delivering respectively. It is relatively expensive because of the special construction required for the flexible cylinder and anchor.

None of these pumps has been used in India in the field. Results of field trials elsewhere are not known to the author.

4. The present work—organisation and approach

The review of previous work (§ 3) shows that there is no detailed documentation of information as to which components of the deepwell handpump can break down and the nature and frequency of such breakdown. For shallow well handpumps, Majumder and Sen Gupta (undated) give the number of replacements of various components in the Calcutta region over a period. Even this limited information was not readily available for deepwell handpumps. What information there was, was sketchy, qualitative and in some cases apparently even false. A 1977 publication (Pacey 1977) says, for example, that 'many pumps in South Asia suffer from some or all of the following defects: (i) poor quality cast iron (very widespread, often due to high phosphorus content); (ii) roughly finished cylinders, cylinder bore uneven; (iii) use of cast iron cylinders instead of brass...; (iv) no protection from rust, parts often badly corroded before the pumps are even installed; (v) excessive wear on leather washers because of (ii), (iii) and (iv); (vi) poor screw threads; nuts and bolts will not stay together; (vii) roughly drilled pivot holes; (viii) no provision for lubrication', and goes on to say that 'nuts and bolts sometimes arrive with incompatible threads'!

The approach of the Working Group was therefore to first determine the 'failure mode' distribution, then to identify the causes of each component failure, consider remedies and evaluate them through tests in the laboratory and in the field.

5. The modes of failure

The ways in which a handpump can break down are defined as the modes of its failure. An *in situ* examination of 60 pumps in two districts of Karnataka was conducted (Gururaja 1976) by the Working Group. 38 of these pumps were not working, and the modes of their failure were determined by either direct observation (breakdown of above-ground components) or inference (breakdown of below-ground components). Based on this, Gururaja (1976) arrived at the failure mode distribution shown in figure 6. It shows that the largest number of pump breakdowns are characterised by the disconnection of plunger rod lengths at the joints (the individual percentage frequencies add up to more than 100 since many pumps showed multiple modes of failure).

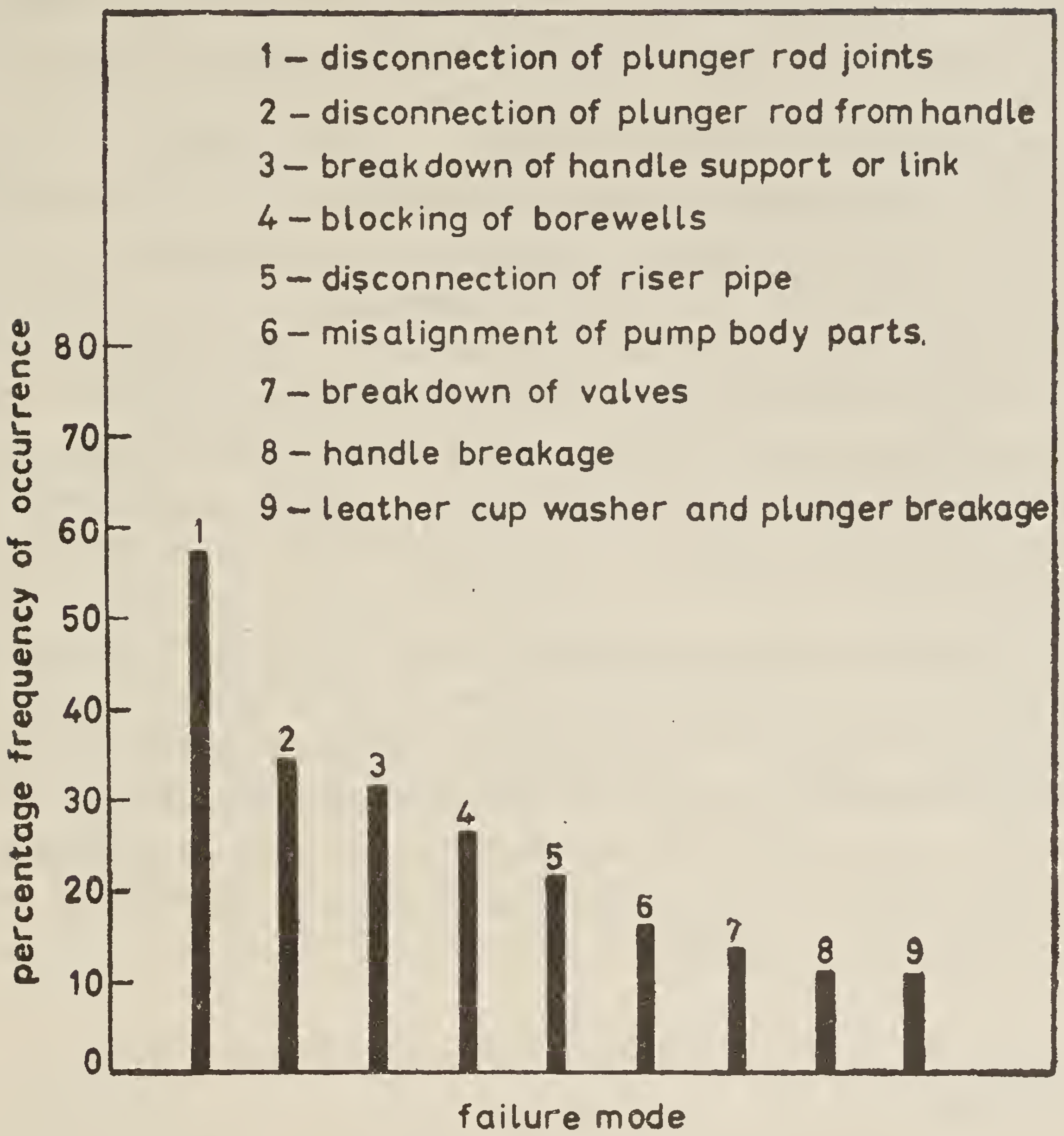

Figure 6. Failure mode distribution (Gururaja 1976) from a 32-pump sample

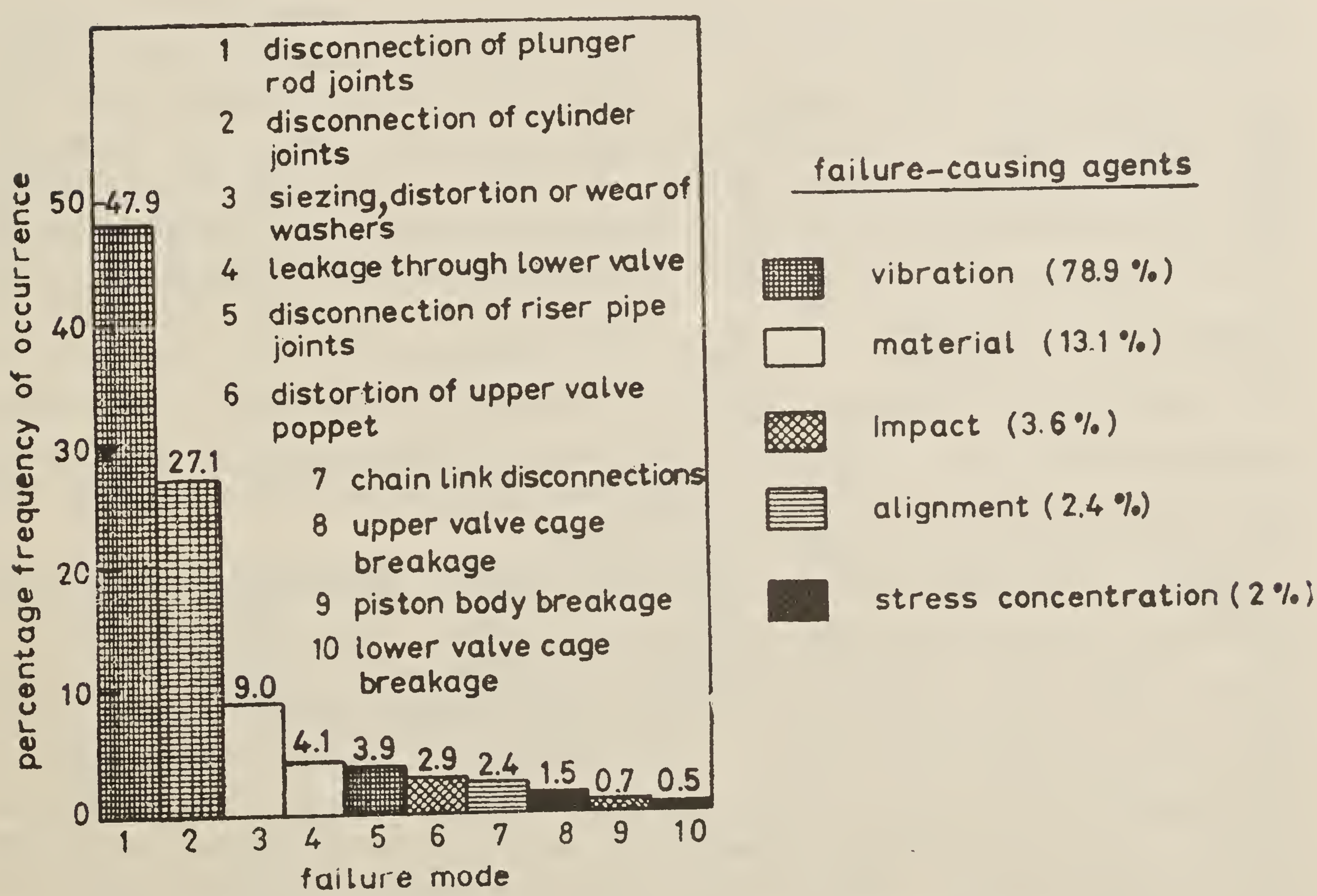

Figure 7. Failure mode distribution.

A little later, the present Working Group decided to survey a larger sample of pumps. Since a precise *in situ* determination of the mode of failure involves heavy expenditure of time and money in travelling and in lifting many pumps out of their borewells, an alternative method was adopted. In this method, the repair records maintained by the Public Health Engineering Division of the Karnataka Government were scanned, the components replaced during the repair of each pump ascertained, and the mode of failure inferred therefrom. A total of 413 pumps, each of which had broken down at least once and repaired, were analysed in this manner, and the new failure mode frequency distribution shown in figure 7 was obtained. In this analysis too, the repair records revealed that some of the pumps had broken down in a multiple mode, but it was possible to identify in each case the primary mode which caused the breakdown. Only these modes were considered for determining the distribution.

The new distribution confirms Gururaja's earlier conclusion (figure 6) that plunger rod disconnections constitute the major mode of failure. Ten modes of failure in all were identified from the repair records. Three of them (modes 1, 2 and 5 occurring with a combined frequency of 78·9%) concern threaded connections. The other modes have to do with other components, the most frequent one concerning the leather cup washers. In the following paragraphs the physical causes behind each mode of failure are examined.

6. Causes of failure

6.1 *Unscrewing of threaded connections*

Threaded connections are very extensively used in handpump assemblies: in a typical assembly where the pump is situated 20 m below the ground, there are on an average nine threaded joints on the plunger rod alone; others are to be found on the riser pipe, cylinder, piston and in the pump head. Any of the plunger rod joints may come apart. The most probable spot at which the riser pipe gets disconnected is where it is screwed on to the pump head, and if this happens, the combined weight of the pump, riser pipe and the water in it will be transferred suddenly on to the plunger rod *via* the piston. The rod is then likely to break and the pump and pipe fall into the borewell. A plunger rod disconnection, on the other hand, is not so disastrous, but the pump will have to be lifted out of the well for repair unless the disconnection is at a joint above the ground. Disconnection of the cylinder from the riser pipe, piston from the plunger rod or piston body from the upper cage also require the pump to be lifted out for repair.

Threaded connections tend to loosen when they are subject to cyclic loading, especially in the presence of large-amplitude vibration. This is because in such a situation there will be relative longitudinal motion between the components of the joint, and the mutual stress at the contact surfaces on the mating threads will be relieved during one half of each cycle. The friction at the contact surfaces, which is proportional to the normal force, will then decrease or vanish, and so will the resistance against unscrewing. Cumulative unscrewing over a length of time finally leads to disconnection. Factors which increase the frictional resistance against unscrewing are (i) larger diameter of the joined parts, (ii) greater joint length, (iii) higher

load on the joint and (iv) higher coefficient of friction between the contact surfaces. The first two increase the contact area, and the last two the magnitude of the frictional force.

Cyclic loading of the plunger rod is inherent in the handpump because of the reciprocating nature of operation. The reciprocating frequency of about 1 Hz is however too low to cause vibrations in the plunger rod or riser pipe. The vibrations of the plunger rod (longitudinal as well as lateral) are caused by the impact of the poppets on the valve seats during closure, of the handle against the walls of the head at the extremities of oscillation, or of the piston against the lower valve or upper reducer when the plunger rod length is not within proper limits. Shaking of the pump head during operation due to loosening of the bolts connecting it to the casing pipe flange also cause vibrations of the plunger rod as well as of the riser pipe.

It is difficult to calculate the natural frequencies of the plunger rod lengths, mainly because the degree of fixity at each joint is unknown. However, since the rod carries the load on the piston, the inertia will be high and since the support at the joint can be considered to yield during that part of the cycle when the stress between contact surfaces is relieved, the stiffness will be low. Low natural frequencies result under these conditions.

6.2 *Wear, distortion or siezing of leather cup washers*

The leather cup washers, commonly called 'leather buckets' in handpump terminology, have typically the section shown in figure 8. Two of them are used in each piston, and their function is to form a seal during the upward stroke between the two sides of the cylinder separated by the piston. The cost of one bucket is about Rs 3, but its replacement costs Rs 200 to 300 due to the labour involved and the transport of lifting devices to the site. The three ways in which the buckets fail to perform satisfactorily are analysed below.

6.2a *Wear* The periphery of the bucket is subject to friction, at least during the upward stroke of the piston. The bucket therefore wears out progressively and its sealing action becomes less and less satisfactory with time, leading to a higher 'slip'. The wear is quicker if the water contains grit.

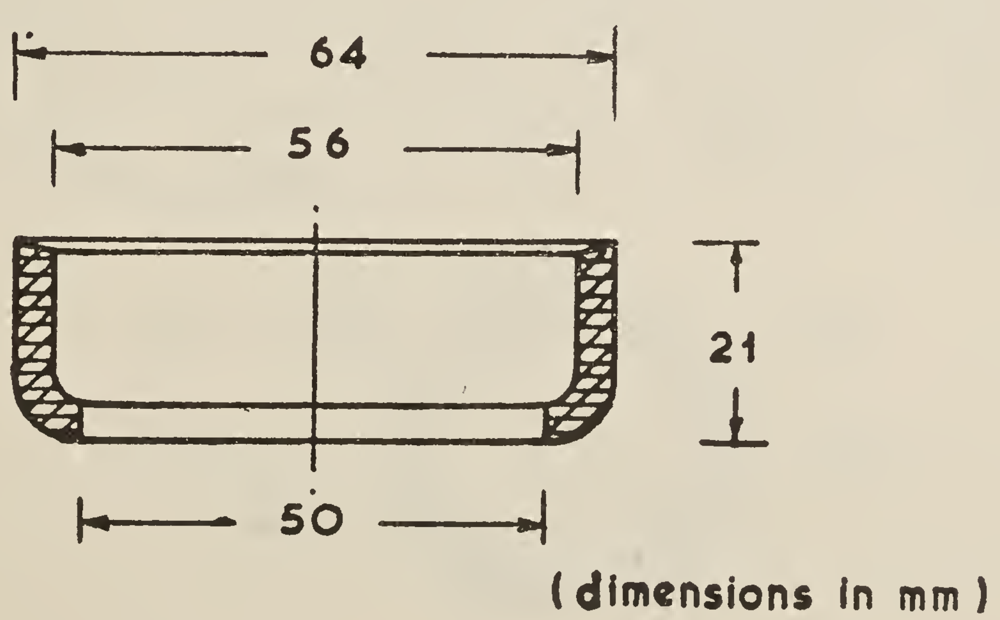

Figure 8. Typical leather bucket in section

6.2b *Distortion* The bucket is subject to a differential pressure of the order of 2 to 3 kg/cm^2, depending on the depth of the water table. This pressure differential is what causes the lip of the bucket to press against the cylinder wall and form a seal. If the clearance between the piston body and the cylinder wall is not small enough, or the leather not thick enough, this pressure differential causes the bucket to extrude through the clearance. The process of extrusion is aided by the friction on the bucket periphery during the upward stroke of the piston. Moreover, if wear reduces the thickness of the leather sufficiently, distortion may occur in a bucket which was good enough initially.

6.2c *Siezing* All leathers, when under water, absorb some of it and expand in consequence. Vegetable-tanned leathers generally absorb less water than chrome-tanned ones (Wilson 1941). The leather buckets of a handpump, therefore, become larger after the pump is installed. The expansion continues over several days. If, initially, the bucket is not smaller than the cylinder bore, after expansion it will press against the cylinder wall and frictional resistance will develop against the downward stroke of the piston. The piston normally descends due to the combined weight of itself and the plunger rod. In cases where the expansion is too large or where the initial clearance between the bucket and cylinder bore is too small, this combined weight may be balanced by the frictional resistance. There is no way of forcing the piston down since the roller chain in the present form of the pump head does not transmit a thrust.

Siezing of buckets is a problem which occurs in the first few days of installation of the pump. Experiments (§ 8.2a) show that most of the swelling takes place in the first five days. If the bucket does not sieze during this period, it will continuously wear during operation, which balances the swelling.

6.3 *Leakage through the lower valve*

The lower valve is of the poppet type, the poppet being lined with a rubber disc on its underside to form an effective seal (figure 2). The rubber disc is normally 6 mm thick, cut out of commercial sheeting. After some 5–6 months of operation, the disc develops cracks, typically as shown in figure 9. The cracks grow rapidly and extend over the entire thickness of the seal, but are confined to the stressed region (i.e., the region which comes in contact with the seating). The width of the cracks may go upto 2 mm. As the cracks develop, leakage of water from the pump back into the well increases, leading to a decrease in discharge as well as emptying of the pipe after stoppage of pumping, so that a large number of strokes are necessary

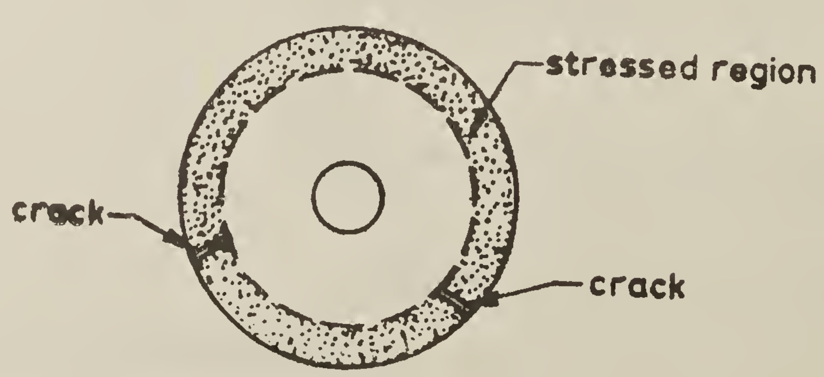

Figure 9. Cracking pattern of rubber seal.

before water is delivered again. The leakage may finally be so heavy that pumping stops altogether.

A large volume of information is available on the degradation of rubber (Blow 1975) thanks to the needs of the tyre industry. Vulcanised rubber products, in common with many other polymeric hydrocarbons, undergo degradation during storage and during use due to oxidative reactions. These reactions are very complex and not well understood and are believed to involve breaking of molecular chains and cross-links caused by factors like mechanical stress ('flexing') or light, later propagating as chain reactions through oxidation. Dissolved oxygen is present in water. Oxygen (as also the small amounts of ozone present in the atmosphere) can attack the rubber polymer direct. The rate of oxygen attack is increased by heating or by the presence of heavy metals like copper or manganese ('rubber poisons'), leading to a rapid loss of elasticity and tensile strength. Intermittent stress in the presence of oxygen causes cracking ('flex cracking'.)

The lower valve rubber seal is in constant contact with the brass poppet which may have a copper content of between 60% and 95%. It is also subject to intermittent stress, being under compression during the downward stroke when the water column in the riser pipe is supported by it and unstressed during the upward stroke. Commercial rubber sheeting contains general purpose antioxidants, which are not particularly effective under a combination of intermittent stress and rubber poisons. Rubber seals for the lower valve made of such sheeting therefore lose strength and elasticity and crack soon under intermittent stress.

6.4 *Distortion of upper valve poppet*

Like the lower valve, the upper valve is also of the poppet type (figure 2), with the difference that the brass poppet is not lined. The poppet rises inside its cage to let water into the delivery side of the cylinder during the downstroke of the piston and settles on its seat with an impact at the beginning of the upstroke. Over a period of 5–6 months, this repeated impact results in the deformation of the poppet disc as shown in figure 10. The deformation might eventually enlarge the disc diameter to such an extent that it gets stuck in the upper cage, and pumping ceases.

The poppet experiences a differential pressure of around 2 to 3 kg/cm^2 (20 to 30 metres of water column) at the start of the upward stroke of the piston. Assuming a disc diameter of 45 mm, poppet weight of 1 kg and a fall of 15 mm and ignoring the drag, the poppet acquires a momentum of 3·8 mkgf/s or kinetic energy of

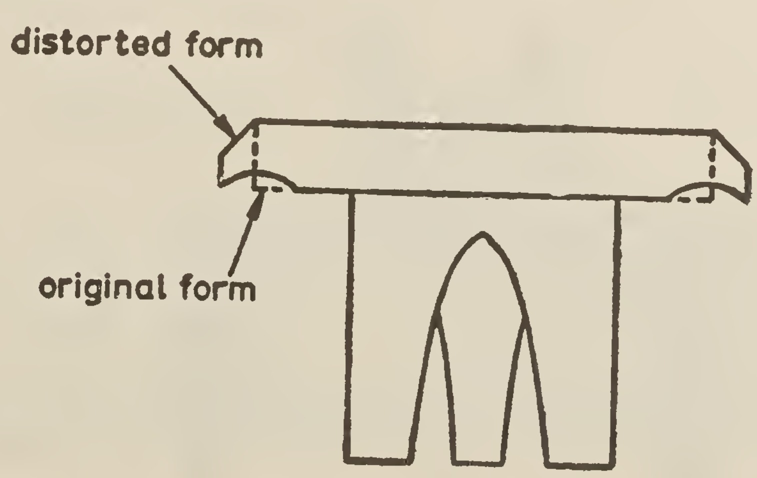

Figure 10. Distortion of upper valve poppet.

0·75 kgfm just before full valve closure (under a pressure differential of 3 kg/cm²). This momentum is destroyed at the moment of closure and the energy is dissipated in the deformation of poppet and valve body and as sound. The energy absorbed by the poppet over about 3 million cycles (corresponding to operation of the pump for six months at the rate of 5 hours a day) distorts it enough to render the pump inoperative.

6.5 *Disconnection of chain*

Although the roller chain in the pump head eliminated many problems associated with the earlier four-bar link mechanism, it now appears to have a problem of its own. The chain is fairly rigid in the transverse direction, though not designed to take a transverse load. Manufacturing tolerances being large in handpumps, one can always expect that the plunger rod axis does not lie in the plane of oscillation of the handle. The offset between the two is greater in some cases, smaller in others. The chain is therefore subjected to some bending moment, which is resisted by forces generated at the ends of the link pins. The pin heads gradually wear out, and the links get disconnected. The problem is aggravated by lack of lubrication. Another disadvantage of the chain is that, as noted in § 6.2c, it cannot transmit a thrust, so that the downstroke of the piston should take place purely due to the self-weight of the piston-plunger rod assembly. If, therefore, the leather buckets swell against the cylinder wall, the pump will be rendered inoperative. Disconnection of the chain links, however, in itself is not so serious as the modes of failure discussed earlier. The villagers usually improvise, removing the affected link pin and substituting it with another pin or a bolt or even a nail.

6.6 *Breaking of the valve cages and piston body*

The function of the upper cage is to retain the poppet in the upper valve as well as to connect the piston body to the plunger rod, while the lower cage has just to retain the poppet in the lower valve. Each cage has four arms with sharp corners (at A in figure 11 which shows the upper cage). The breaking of the cage always occurs at this corner. The static load on the upper cage is due to the differential pressure on the piston (and is of the order of 60–70 kg for water level 20 m below ground). In addition, the impact of the upper valve poppet on its seating is transmitted to the arms of the cage. The lower cage, on the other hand, does not carry any static

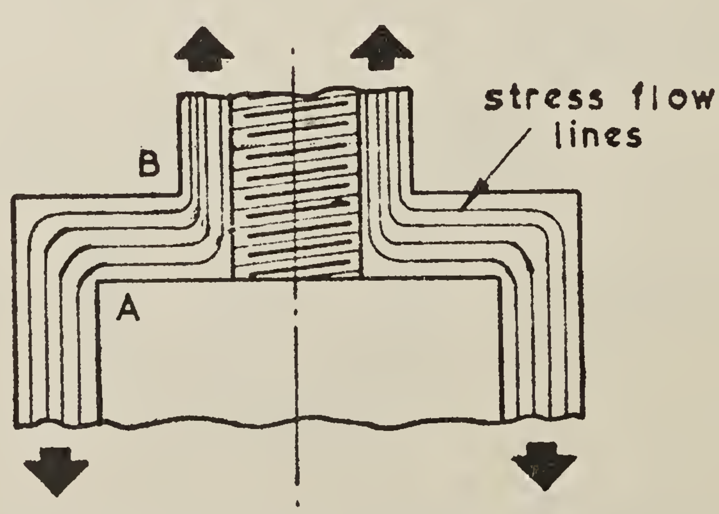

Figure 11. Stress concentration at the corners A and B of the upper cage.

load, nor is the impact of the poppet transmitted to its arms. If, however, the piston is not properly positioned when the pumpset is installed, the piston body may hit the lower cage towards the end of the downward stroke. The cage or the piston body may break as a result.

The average stress in each arm due to the static load is of the order of 50 kg/cm^2, and even allowing for the impact, the average stress is within the allowable limit. Figure 11 shows the stress flow lines in the arms of the upper cage. The lines tend to bunch up and cut very close to re-entrant corners. This happens with the inside of the corner A and stress concentration develops at this point. A minute crack starting here will rapidly grow because there will be an increasing stress concentration at the inner end of the crack, and finally the arm breaks. When all the four arms of the upper cage break, the piston gets disconnected from the plunger rod. If it happens for the lower cage, the poppet of the lower valve will not be constrained to remain in the valve.

6.7 *Other defects*

There are some defects in handpumps which have not yet qualified for inclusion under the modes of failure because before they can render a pump out of order, the pump will fail in one of the modes of figure 7. One of these defects is that the two ball bearings which support the handle on its fulcrum pin wear out due to lack of lubrication. The balls fall out as the gap between the outer and inner races increases, and the handle wobbles during operation. Another defect is that the steel plate of the head gives way beneath the points which support the fulcrum pin of the handle. The bearing pressure is apparently too large for the material. This event throws the alignment of the moving parts of the head out of gear, leading to other problems. A third defect is the inadequate thickness of zinc coating given to the plunger rods. The thickness at present is 8μ, which according to Indian Standard Specifications (Anon 1970), is the minimum for 'mild service conditions, involving exposures indoor, with a normally warm dry atmosphere'; hardly the conditions in which the plunger rods of a handpump work. The coating gives little protection, and the plunger rod rusts. Rare cases of plunger rod fracture occur as a result, but as already remarked, other modes of failure normally intervene before this happens.

Figure 7 summarises the physical reasons behind the modes of failure.

7. Reliability and maintenance of handpumps*

7.1 *Reliability*

The reliability with which a machine is designed to work is determined after considering various factors such as cost, social factors, consequences of failure, general economy etc. Some machines are sought to be built with a very high degree of reliability, e.g., passenger aircraft where it makes a difference between life and death, or reduction gear units of ships where down-time involves huge losses. In

*Part of this section has been contributed by Nagendra Nath.

other cases, the life built into a machine is limited by the tendency of the users to replace them after an interval (e.g., automobiles in the USA) or by the need to provide continued employment to the people engaged in its manufacture.

In the case of handpumps in India, a high degree of reliability is necessary because of the numbers involved (there are at present 24000 pumps in Karnataka alone, increasing at the rate of about 9000 pumps per year), lack of local maintenance, the high cost of maintenance by district-level units and the need for healthy rural drinking water supply.

Data for computing the current reliability of handpumps is not completely available. While the date of installation and dates of subsequent repairs are recorded, the date of breakdown of a handpump is unknown. An important performance parameter like the mean time between failures (MTBF) cannot therefore be directly calculated. The life of a component part of the handpump can likewise only be estimated. Based on discussions with engineers and users, an estimate of the mean life of the components which figure in the modes of failure has been made and is presented in table 1.

The frequencies of occurrence of the different modes of failure (figure 7) can be used to estimate the reliability of the handpump (table 2) over the period during which the 413 pumps concerned failed (this period is again uncertain, but is estimated

Table 1. Mean life of the components

Components	Life in weeks
Plunger rod joints	10
Cylinder joints	30
Leather buckets	30
Lower valve seal	30
G I pipe joints	50
Upper valve poppet	30
Chain	50
Upper valve cage	100
Piston body	100
Lower valve cage	100

Table 2. Reliability factors for the handpump components

Component part	Reliability factor
Chain	0·976
Plunger rod joint	0·521
Cylinder joint	0·729
G I pipe joint	0·961
Upper valve cage	0·985
Upper valve poppet	0·971
Piston body	0·993
Leather bucket (upper)	0·91
Leather bucket (lower)	0·91
Lower valve cage	0·995
Lower valve seal	0·959

to be about six months). The reliability factor of each component can be taken to be $(1-f)$, where f is the frequency of its failure.

All the component parts in the handpump are logically connected in series, since the failure of any one of them means the failure of the pump as a whole. The overall reliability of the pump is simply the product of the individual reliability factors, amounting to 0·267. The probability of pump failure is therefore 0·733, or 73·3% over the period for which the frequencies of figure 7 are valid (i.e., about six months). In other words, left unattended, 73·3% of the pumps will fail in about six months.

It is obvious that a major improvement in reliability can be achieved by just improving the reliability factors of the plunger rod joints and cylinder joints. However, the other component parts should not be ignored, since the reliability factors are much smaller than indicated in table 2 if one considers longer periods (e.g., 5 years).

7.2 *Maintenance*

The proportion of pumps working at any given time depends on the speed with which breakdowns occur and are repaired.

Let N_0 = total number of pumps at time $t=0$ (all assumed to be working),
i = rate at which new pumps are installed,
r = rate at which broken down pumps are repaired,
N = total number of pumps existing at any time t,
p = total number of pumps in working order at time t
and m = mean time between failures of a pump.

All these quantities are connected by the relation

$$(dp/dt) + p/m = i + r, \tag{1}$$

with the initial condition $p=N_0$ at $t=0$. Two cases can be considered, when (i) r=constant and (ii) r increases linearly with time, starting from zero. The former occurs when the handpump installation programme has progressed quite far and the full maintenance organisation has been established, whereas the latter is valid when the programme is at its beginning and no funds have been allotted for maintenance.

Case (i): r=constant

The solution of the differential equation for this case is

$$p = [N_0 - m\,(i + r)] \exp(-\,t/m) + m\,(i + r). \tag{2}$$

The proportion of pumps in working order is

$$p/N=\{[N_0/mr-(i/r)-1] \exp(-t/m)+(i/r)+1\}/[N_0/mr+(i/r)\,(t/m)], \tag{3}$$

where the relation $N=(N_0+it)$ has been used. When the installation of the planned total number of pumps is complete, i becomes zero, and equation (3) reduces to

$$p/N_0 = [1 - (mr/N_0)] \exp(-\,t/m) + (mr/N_0), \tag{4}$$

where N_0 is the total number of pumps installed. Equation (4) shows that after new installation activity has ceased, the proportion of working pumps decays exponentially to reach an asymptotic value of mr/N_0.

This result helps one to estimate m, the mean time between failures (MTBF). At the beginning of July 1977, the Tamil Nadu Water Supply and Drainage Board had installed 14,210 pumps in Tamil Nadu and had set up a maintenance organisation big enough to keep almost all the pumps working. About 270 pumps would be out of order at any given time ($p/N_0 = 0{\cdot}98$), and every week about 740 pumps would be repaired. Assuming that the asymptotic value of p/N_0 had been reached, m works out to about 19 weeks. This figure for the mean time between failures is of the same order as estimates by users as well as field engineers. Further, if we consider only the 413 pumps which provided the data for the reliability computation (§ 7.1) and apply equation (4) with $r=0$, then

$$p/N_0 = \exp(-t/m). \tag{5}$$

Substituting $p/N_0 = 0{\cdot}267$ and $t = 6$ months (26 weeks), equation (5) gives $m = 19{\cdot}7$ weeks, which closely agrees with the estimate from the Tamil Nadu data. Figure 12 shows the maintenance capability required to keep all the pumps working, as a function of the total pump population and the MTBF. With the current Karnataka pump population of 24,000, the repair capability required is 1200 pumps per week, assuming the current MTBF to be 20 weeks and that no new pumps are installed. Against this, the current Karnataka capability is 550 repairs per week (Subbaiah 1979). New pumps are being installed at the rate of about 170 per week to meet the ultimate objective of providing a pump for every 300 people. A total of 90,000 pumps are required for the current rural population of 27 million, and 4,500 pumps will have to be repaired every week to keep all of them working. The average cost per repair comes to Rs 180 (during the year 1978–1979, 29,858 repairs were carried out in

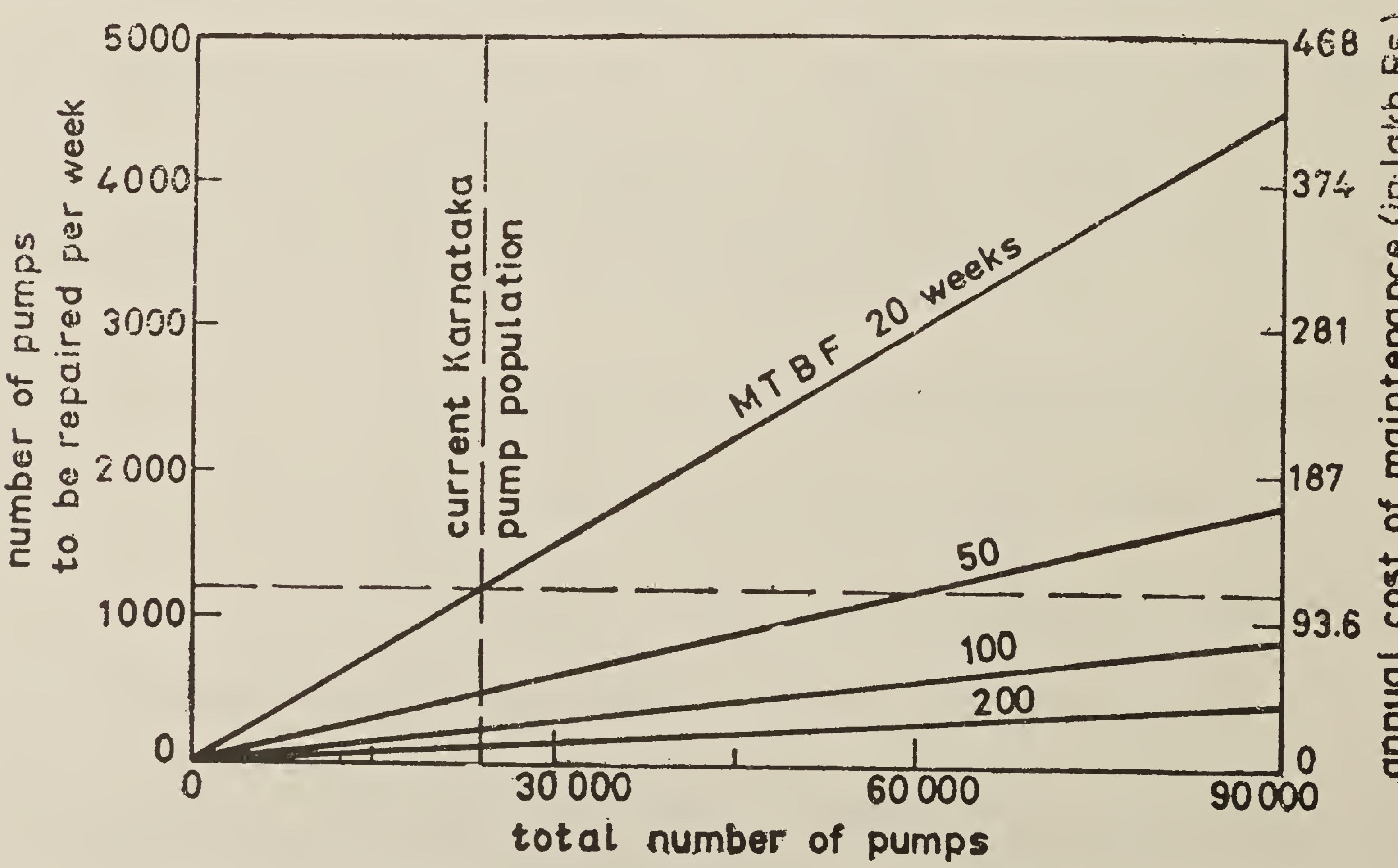

Figure 12. Maintenance capability required as a function of mean time between failures (MTBF) and pump population.

Karnataka at a cost of Rs 53·2 lakhs). The annual cost of maintenance of 90,000 pumps would therefore be Rs 4·21 crores at current prices, if the MTBF is not increased. The cost will come down ten-fold to Rs 41·7 lakhs with an MTBF of 200 weeks.

Figure 13a shows the rate of decrease in the proportion of working pumps for some representative values of N_0/mr and i/r. The current values of these parameters in Karnataka are respectively 2·18 and 0·31 represented in curve 4. It is seen that with the current rates of repairs and new installations, if the MTBF is not increased, only

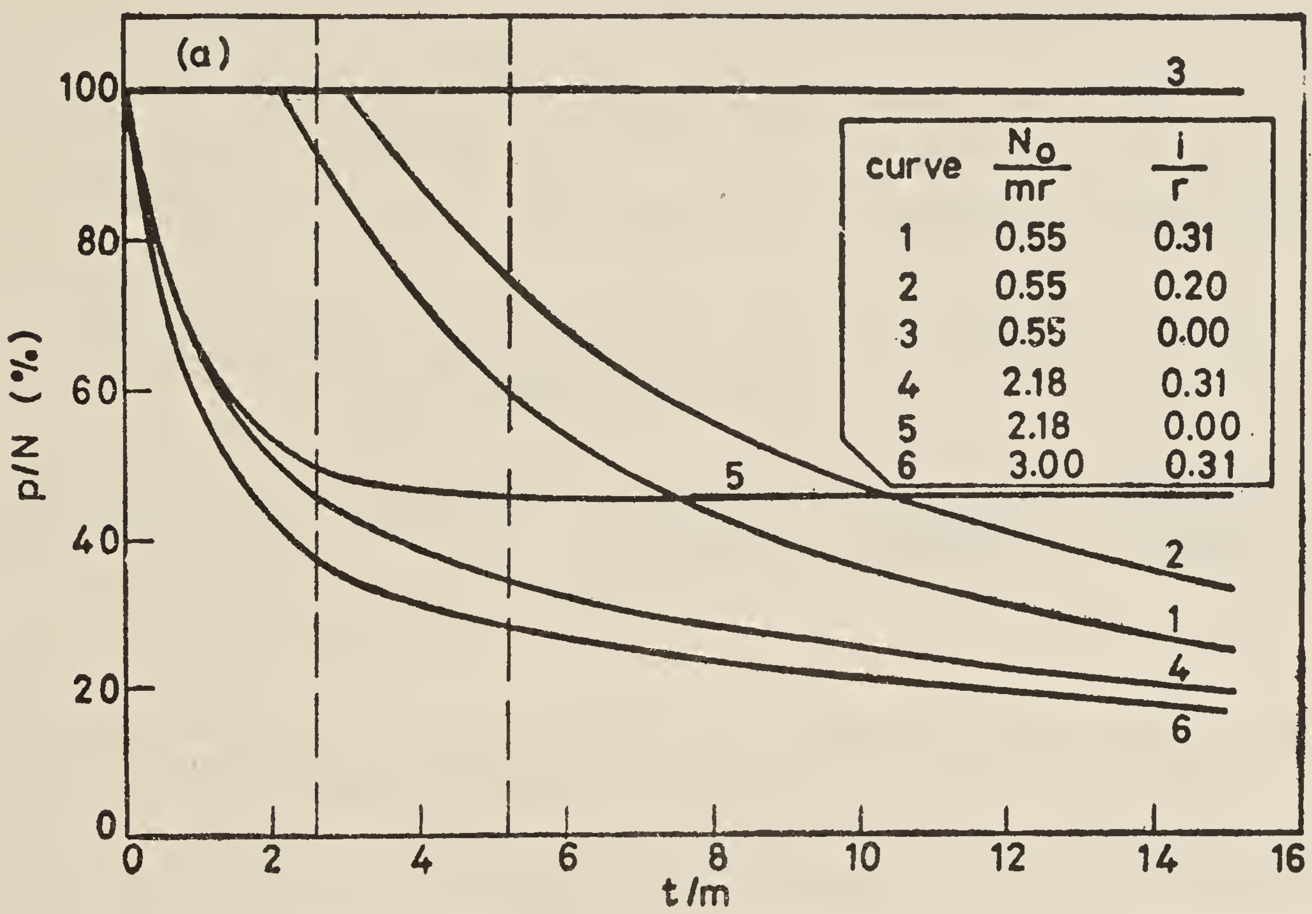

Figure 13a. Decay of working pump population, r = constant.

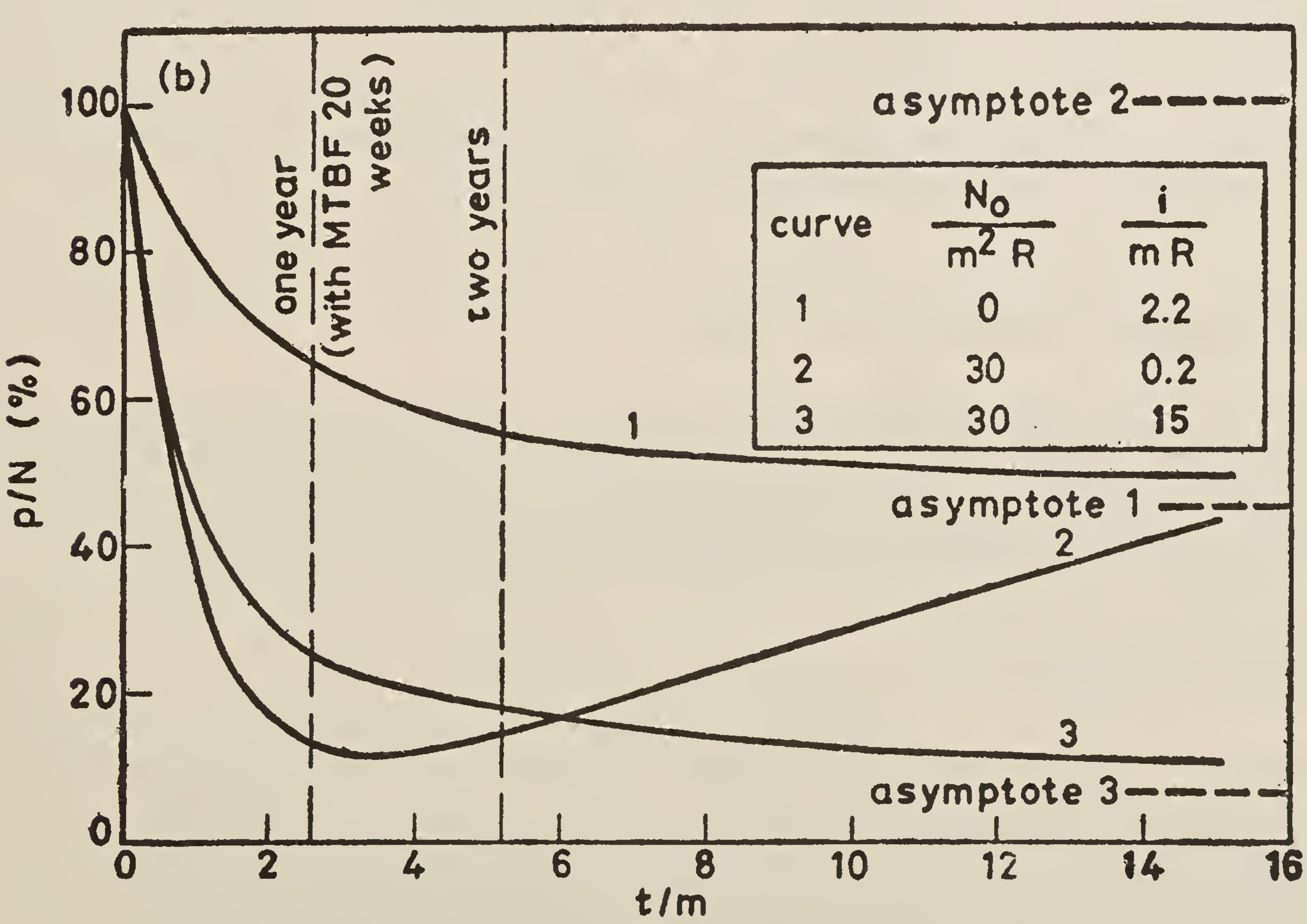

Figure 13b. Decay of working pump population, r/t = constant.

46% of the pumps will be working after a year from now and 35% after two years (assuming that all the 24,000 pumps are working now). Curve 5 shows the decay in working pump population if no new pumps are installed ($i=0$) from now on. The number of working pumps stabilises at 46% after two years if the current repair rate of 550 per week is maintained. Curves 1, 2 and 3 show the situation when the total pump population is 90,000 (all working to start with) and the MTBF is increased to 300 weeks, with the repair rate at the current level.

Case (ii): $r=Rt$

The solution of equation (1) in this case is

$$p=[N_0-m\ (i-Rm)]\ \exp\left(-t/m\right)+m\ [i+R\ (t-m)], \tag{6}$$

and the proportion of working pumps is given by

$$p/N=\frac{[(N_0/m^2R)-(i/mR)+1]\ \exp\ (-t/m)+(i/mR)+(t/m)-1}{(N_0/m^2R)+(i/mR)\ (t/m)}. \tag{7}$$

As $t/m\to\infty$, $p/N\to mR/i$, and therefore for all pumps to be working, the rate of increase in maintenance capability should be

$$R=i/m. \tag{8}$$

Figure 13b shows how the proportion of working pumps varies with time for three situations in this case. Curve 1 corresponds roughly to the situation in Karnataka with $t=0$ representing the beginning of the Government's handpump programme (in 1973), taking the average values of the variables over the past six years. The working pump population stabilises at 45·5% (*cf.* curve 5, figure 13a) asymptotically. Curves 2 and 3 represent other hypothetical situations. In the former case, p/N decreases rapidly at first, but with steadily increasing rates of repair, passes a minimum and reaches 100% at $t/m=38{\cdot}5$, after which a reduced rate of repair will keep all pumps working. Such is the case whenever $i/mR<1$. Curve 3 corresponds to the case where the repair rate is never sufficient to increase p/N, which decreases steadily to reach an asymptotic value of 6·7%.

8. Remedial measures and laboratory tests

The physical causes behind the modes of failure discussed above also give clues to measures which are likely to improve the reliability of handpumps. Some alternatives and laboratory tests on them are described in the following paragraphs.

8.1 *Threaded connections*

Measures which could be adopted to improve the reliability of threaded connections involve (i) devices which positively prevent relative rotation of the joint components or (ii) devices which increase the friction at mating surfaces in the joint. In the first category come devices like slotted nuts, but they need holes to be drilled in the plunger rod and sometimes in the collars which generally is not possible in the field. Besides,

such devices cannot be used for the GI pipes because of the leakage problem. In the second category, possibilities like increasing the component diameters or lengths are excluded because of limitation on borewell size and tooling required. A common method of increasing friction is to load the joint using locknuts, which in fact was already being done in handpumps. But locknuts are unreliable because of the difficulty in obtaining the initial tightening load (Shigley 1972) and the fact that the strain induced in the joint components is readily relieved by wear or rust formation at the interface between the locknut and collar.

8.1a *Plunger rod joints* After considering available information, it was decided to study the suitability of spring lock washers for improving the plunger rod joints. A compression test was conducted on commercially available 12 mm spring washers, and it was found that the load required to compress the washer fully was 45 kg. This is about the magnitude of load on a joint in a handpump where the water table is 20 m below ground. Thus using a spring washer will double the load on the joint, doubling the normal friction between the contact surfaces, and in addition providing a residual stress when the rod is subject to vibration within certain limits. Besides, the residual stress prevents the yielding of the support at the joint, increasing the effective stiffness of the plunger rod length. The natural frequency of the rod increases as a result, and low frequency vibration will not be excited. Spring washers keep threaded connections intact in motor cycles, scooters and other automobiles.

An impact rig was built to assess the relative improvement in joints with spring washers over ordinary joints as well as other joints. Figure 14 shows the rig, in which plunger rod joints using (i) only locknuts, (ii) locknuts and spring washers, (iii) flanges and (iv) locking side plates mounted between a fixed bottom bar and a movable top bar. The top bar is given blows with a hammer driven by an eccentric at 72 rev/min which is of the order of the frequency of handpump operation. The conventional joint (with locknuts) separated completely after an average of 15–20 minutes of test (the maximum was 45 min), while the joint using spring washers as well as the other two kinds tested remained intact even after 7 hr of continuous testing. The mean time between failures of plunger rod joints in the field is not known precisely, but is estimated to be ten weeks. If this is linearly correlated with the test MTBF, any of the other three joints will have a minimum life of two years. The actual life is likely to be much more, since the joints have not been tested till they separate.

Of the three types of joints tested, the ones using spring washers have been selected for field trials because of the ease with which they can be assembled. Other advantages are the low cost and ready availability of the spring washers. It was expected that corrosion might pose a problem, but field trials indicated that this was not so. Apparently, the zinc coating on the galvanised nut and collar between which the spring washer is compressed acts as a large anode with respect to the washer which therefore enjoys automatic cathodic protection against corrosion.

8.1b *Pipe joints* For the joints of the riser pipe and the cylinder, spring washers of suitable size are not readily available. The method selected for these joints was to insert cotton string between the mating threads. Cotton string is normally used in domestic water supply lines to prevent leakage, but its function in the present case

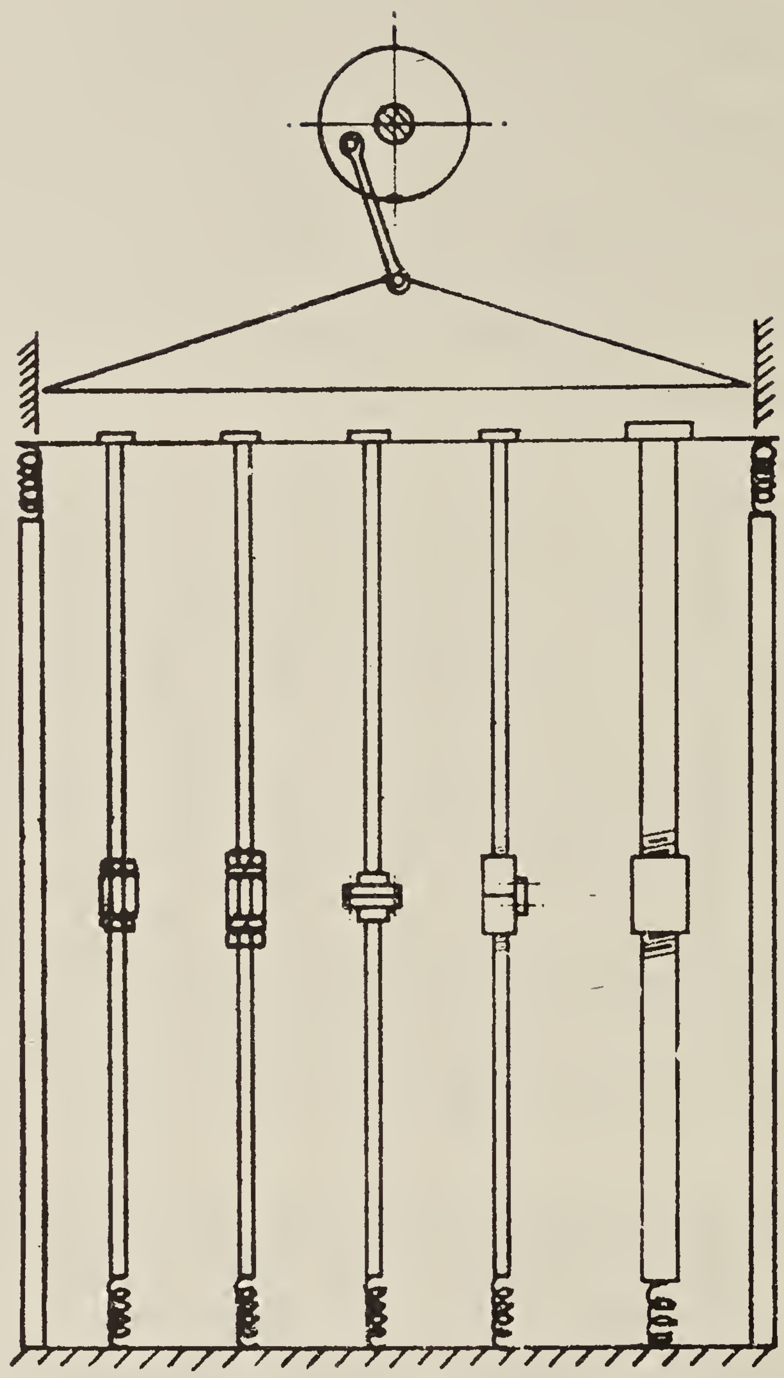

Figure 14. Impact rig for testing plunger rod and pipe joints.

is to increase friction. The coefficient of friction between two steel surfaces under wet contact is 0·05, but that between cloth or plastic and steel is between 0·1 and 0·15. Data for friction between cotton string and steel are not available, but it is reasonable to assume that the same value as between cloth and steel is valid. There is thus a two to three-fold increase in frictional resistance against unscrewing if cotton string is wound over the threads of the riser pipe before it is screwed into the collar. A pipe joint made in this way was also tested in the impact rig (figure 14) and it remained intact after a test for seven hours.

8.1c *Other measures* Since vibration is the root cause of disconnections of threaded joints, it is worth attempting to reduce it. While the impact of the upper valve poppet cannot be avoided, vibration induced by it would be reduced by a measure being contemplated to avoid its distortion (§ 8.4). The surfaces of the head against which the handle strikes could be lined with leather to soften the impact. The bolts connecting the head to the casing pipe flange could be fitted with nylock nuts (nuts provided with a nylon ring insert, which has a high coefficient of friction against steel; these nuts are used in motor vehicles, and are available off the shelf in the market) and spring washers to prevent the shaking of the pump head on its foundation.

8.2 *Leather buckets*

Piston packings (of which buckets are of one form), ignoring metal rings, are broadly divided into two classes: fabricated and homogeneous. Fabricated packings are made of fibrous material. Leather (which is three-dimensionally woven collagen fibre), woven cotton duck, canvas or asbestos cloth impregnated with synthetics and leather impregnated with synthetics are used for fabricated packings. Homogeneous packings are made of homogeneous polymers like neoprene, butyl or styrene butadiene rubbers (SBR) and plastics such as teflon or PVC. PVC washers have been found to last longer than leather washers in shallow well pumps in Bangladesh (§ 3.4). However, several types of synthetic washers tried in the deep wells of Karnataka were torn to pieces over a very short period of operation, apparently due to extrusion (§ 6.2b). Synthetic materials generally have a much lower tear strength and abrasion resistance than fabricated ones. Both fabricated and homogeneous piston packings have been used in the oil hydraulic industry, where experience shows that (Stewart 1955) homogeneous packings are successful only when the cylinder surface finishes are very good (roughness maximum $0{\cdot}4\,\mu$ rms), diametral clearance between piston body and cylinder bore is from 0·1 mm to 0·15 mm and piston eccentricity less than 0·1 mm. Cylinders meeting these conditions would be very expensive. On balance, leather seems to be the best material for handpump buckets.

The discussion in § 6.2 suggests that low water absorption and strict tolerances on the bucket size should ensure a good bucket performance. The leather for the buckets comes from cow- or buffalo-hide. Different parts of the hide produce leather of different physical properties (Wilson 1941).

The backbone, butt and shoulder regions of the leather are tough and the fibre there is densely and compactly woven. The remaining part (especially the belly and neck regions) is loose and flabby, has a lower resistance to wear and abrasion and absorbs much more water than the other part. For these reasons, the backbone, butt and shoulder regions of vegetable-tanned leather (which absorbs less water than chrome-tanned leather) are specified for pump buckets by the ISI (Anon 1956). Discreet inquiries, however, lead one to conclude that in the absence of a corresponding stipulation in the contract, manufacturers use the other parts of leather too to make the buckets.

8.2a *Water absorption characteristics of leather buckets* Tests on swelling due to water absorption were conducted on four buckets purchased at random in the market as well as two specially ordered to be made of the butt, backbone or shoulder of buffalo leather. Each bucket was immersed in tap water in a beaker, its circumference at the lip being measured before immersion. The bucket was taken out at intervals of 24 hr, wiped, and after its circumference was measured, immersed again. This testing was continued for about two weeks. The results are shown in figure 15 as a plot of the percentage increase in circumference at the lip (and hence, of the lip diameter) against the duration of immersion. Curves 1, 2, 3 and 4 relate to buckets purchased from the market and curves 5 and 6 to the buckets specially ordered.

It is seen that a major part of the swelling of almost all buckets takes place by the end of five days of immersion. The trend indicates that the buckets purchased from the market expand in circumference at the end of 13 days of immersion by 7·3 to

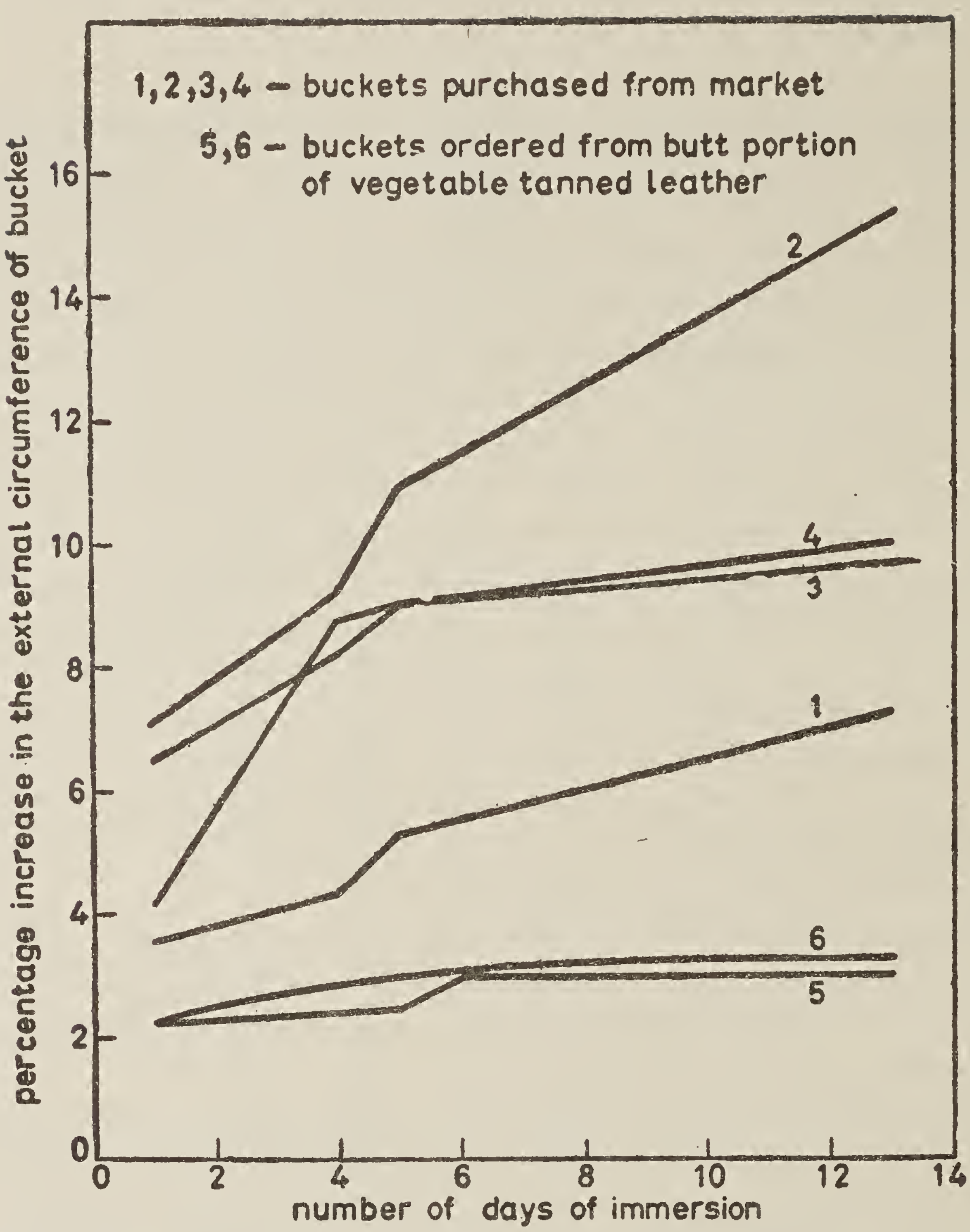

Figure 15. Swelling of leather buckets due to water absorption.

15·4%. Buckets made from denser leather (Nos. 5 and 6) show a maximum expansion of around 3%. Further, even after 13 days, the first four buckets appear to continue to swell, while the two made to order cease their expansion after six days.

At this point, it is not clear why all the four buckets from the market showed large swelling. The butt, backbone and shoulder account for 60–70% of the total leather area, and the proportion should have been reflected in the swelling characteristics of these buckets (if all the leather was used in making the lot). Microscopic tests will shortly be conducted on buckets from the market to determine their regional distribution.

8.2b *Size distribution of commercial leather buckets* Given the fact that all leather buckets absorb water and swell (to different extents depending on the quality), it is obvious that the larger the original diameter of the bucket, the higher the probability that it will seize in the cylinder. In the process of moulding pieces of leather into cups, one can expect that all buckets will not come out with the same size though the same die may be used for moulding. The variations in the finished size are due to differences in the engineering properties between one piece of leather and another, variations in moulding pressures and treatment before and after moulding, etc. In order to ascertain the size distribution of the buckets, 120 of them were sampled

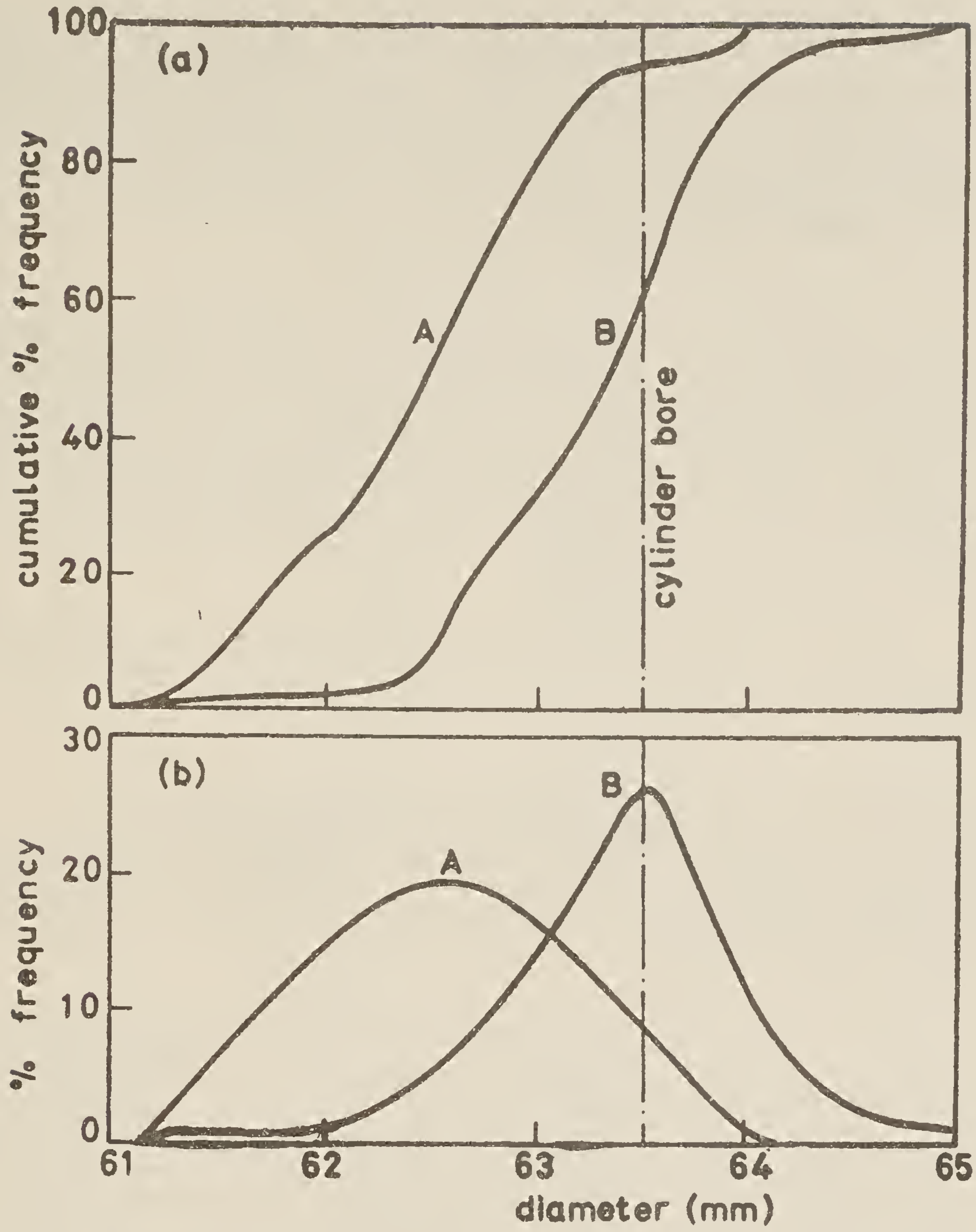

Figure 16. Size distribution of buckets.

out of the stock with the Bangalore division of the Public Health Engineering Department. 36 buckets were made by one manufacturer (designated A) and 84 by another (B). The external circumference of each bucket was measured and the mean diameter calculated therefrom. The diameter distribution is shown in figure 16 separately for the two makes. The cylinder bore diameter is marked on the diagram. From figure 16a, it is seen that 94% of the A buckets are smaller than the cylinder while only 58% of the B buckets belong to this category. Figure 16b shows the proportion of buckets within $\pm 0{\cdot}5$ mm of any given diameter in a sample. This frequency peaks at 62·5 mm for the A buckets and at 63·5 mm for the B. Ignoring a small fraction (3%) of the B buckets, the total spread of diameters (figure 16a) for both the makes is 3 mm (61 to 64 mm for A and 62 to 65 mm for B), which is about 5% of the mean diameter. The central 2 mm range accounts for about 85% of buckets.

Allowing for a 3% swelling (§ 8.2a), the bucket diameter suitable for a 63·5 mm cylinder is 61·5 mm. A 3 mm spread means that a sample of buckets with this diameter as mean will range from 60 mm to 63 mm in diameter. The central 2 mm range includes 60·5 mm to 62·5 mm buckets. The smallest of these buckets expands to 61·3 mm (3% swelling) under water, and the largest to 64·4 mm. Thus the largest buckets exert a little pressure on the cylinder walls. But experience with the A and B buckets where 50% and 92% respectively of the lots exceed the 62·5 mm limit

shows that the proportion of buckets which seize is less than 9% (vide figure 7). 62·5 mm therefore seems to be a safe limit. The smallest buckets, after swelling, still work with a clearance of about 2 mm, which is to be closed by the water pressure during the upstroke of the piston. Laboratory testing is under way to determine the suitability of the lower limit (§ 8.2f).

8.2c *Optimum size of buckets* In order to avoid extrusion, it is desirable to use piston bodies and spacers with a flange diameter of between 62·5 mm and 63 mm. This leaves a maximum clearance of 1 mm, through which the leather buckets cannot get extruded. Besides, if the butt, backbone and shoulder regions of the leather are exclusively used to make the buckets, the resistance against extrusion is much higher than if other parts are used.

8.2d *Field trials* For field trials, the following specifications have been adopted to avoid bucket failure:

(i) bucket diameters to lie between 61 mm and 62·5 mm;
(ii) piston body and spacer flanges to have a minimum diameter of 62·5 mm;
(iii) only the butt, backbone or shoulder parts of cow- or buffalo-leather to be used to make the buckets.

8.2e *Laboratory test rig* To test the performance of the leather buckets and other components inside the cylinder, a closed circuit test rig was fabricated (figure 17). It consists of the actual pump assembly (cylinder, piston, lower valve and upper reducer). A $1\frac{1}{2}$ GI pipe connects the two sides of the cylinder and provides the return path. The piston rod passes out through a stuffing box which prevents leakage of water. An eccentric, driven by an electric motor at 130 rev/min, in turn drives the piston at the same frequency (which is about twice the average frequency of operation of a handpump). Water from the top of the cylinder passes to the bottom through the lower valve during the upstroke of the piston. A valve is provided in the return pipe, and its opening determines the pressure difference between the two sides of the piston during its upstroke. Any depth of water table with which a handpump operates can thus be simulated by adjusting the opening of the valve.

8.2f *Tests on leather buckets* Two buckets obtained by the Bangalore Division of Public Health Engineering as per the specifications in § 8.2d were installed in the test rig and tested for a total of 182 hr, i.e. $1{\cdot}42 \times 10^6$ cycles of operation. Assuming an average of 300 users per pump and a per capita water consumption (Reddy 1979) of 17 litres/day, a handpump operates at 17000 cycles/day (about 4 hr 43 min). The duration of testing therefore is equivalent to 84 days of operation of an actual handpump. The depth simulated for the test was 20 m. The total test duration of 160 hours was spread over a period of five months, during which the pump was filled with water. The buckets were taken out at the end of this period, wiped and their circumference was measured and table 3 gives the results.

The bucket diameters actually decreased, the wear and slight changes in shape more than compensating the expansion. More detailed tests are in progress to determine rate of wear etc.

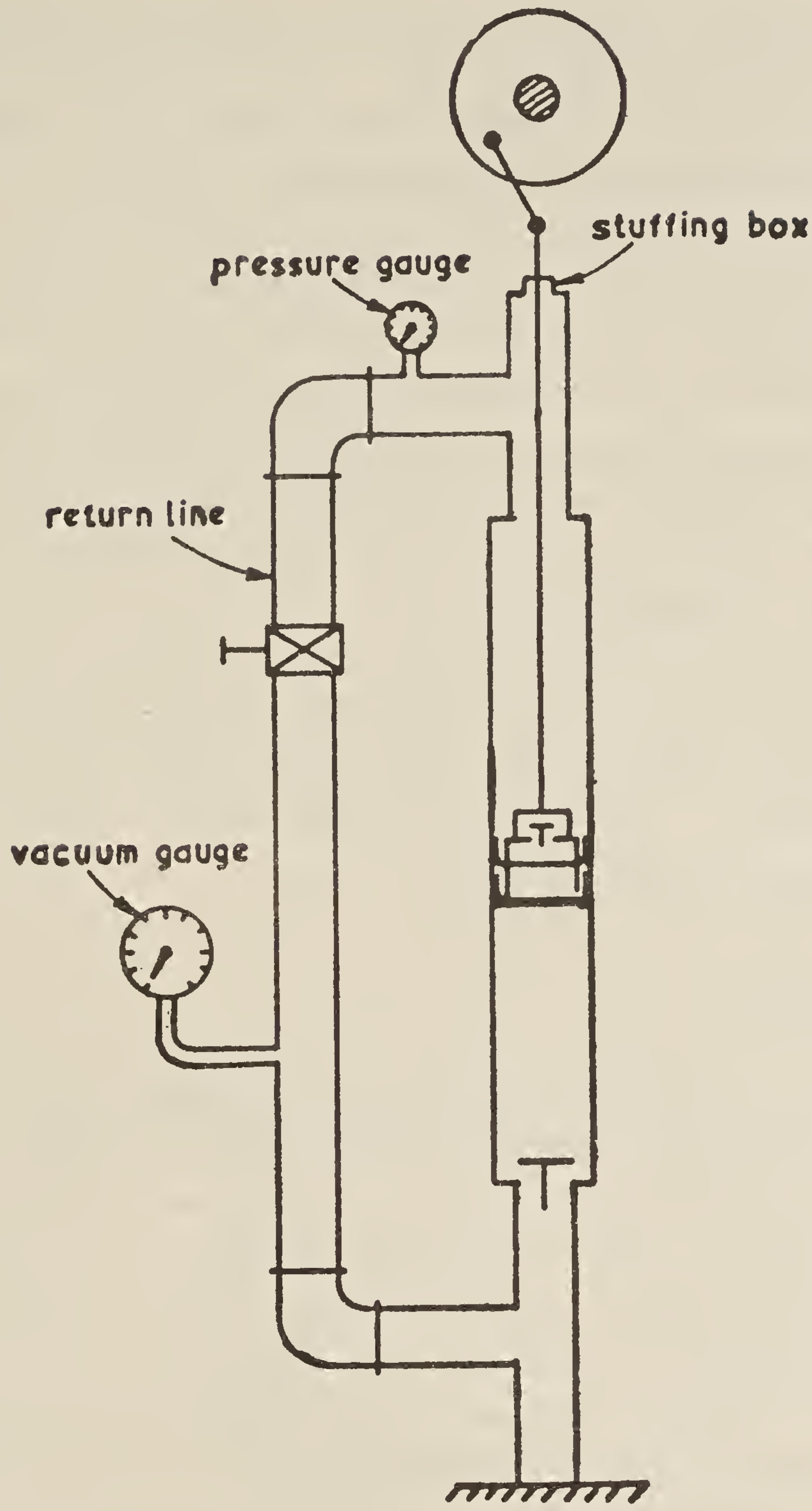

Figure 17. Pump test rig.

Table 3. Laboratory performance of leather buckets

Inner circumference of cylinder = 198·5 mm	Upper bucket	Lower bucket
Initial circumference (mm)	198·0	197·5
Final circumference (mm) at the end of 5 months of testing	195·5	191·0
Decrease in circumference (mm)	2·5	6·5

8.3 *Rubber seals for lower valves*

A large variety of rubber compounds have been developed to work under different situations. As far as lower valve seals are concerned, the initiation and growth of cracks and the tear strength are obviously very important. Natural rubber has better resistance against crack initiation and growth and a higher tear strength than synthetic rubbers such as neoprene or SBR) (Blow 1975). Compounding the rubber

with carbon black (very fine carbon particles, as obtained by burning oil) improves such resistance as well as the tensile strength. Of the large number of antioxidants manufactured in India, Accinox ZA and Accinox HFN are claimed to impart very good superflexing and copper-inhibiting properties to rubber. Accinox DN is also said to be good in this connection. HSL beads are also claimed to possess these characteristics to some extent (this is no reflection on the products of other manufacturers; these products have been named only because literature about them was readily available). Based on available information and discussions with rubber technologists, seals moulded from the following rubber compound have been selected for field trials (figures indicate parts by weight). Natural rubber smoked sheet: 100; HAF Black: 40; zinc oxide: 20; stearic acid: 3; sulphur: 2·5; MBTS: 1·25; accinox DN: 1; HSL: 1·5; process oil: 5.

In addition, a seal moulded from the following compound has been tested in the test rig described in § 8.2e over $1{\cdot}42 \times 10^6$ cycles simultaneously with the leather buckets: Natural rubber smoked sheet: 100; HAF Black: 50; zinc oxide: 5; stearic acid: 1; sulphur: 2; MBT: 2; HSL: 2·5; process oil: 10. The seal has withstood the flexing without developing any crack.

8.4 *The upper valve poppet*

Two measures are being evaluated to avoid the distortion of the upper valve poppet. The first measure consists of providing a water cushion (figure 18) by means of an annular recess in the underside of the poppet flange and a corresponding projection on the valve seat. As the poppet approaches its seat at the beginning of the upstroke of the piston, the water in the gap C (figure 18) is required to be forced out through the ever decreasing clearance between the poppet and valve seat. This will raise the pressure at *C*, and the poppet is slowed down, reducing the impact on it. The piston rod in the test rig has been instrumented with strain gauges and pressure tappings have been incorporated in the valve seat in order to measure the impact and force on the poppet. These experiments are now under way.

The second measure consists of lining the valve seat with leather, the elasticity of which softens the impact on the poppet. This is expected to be field-tested shortly.

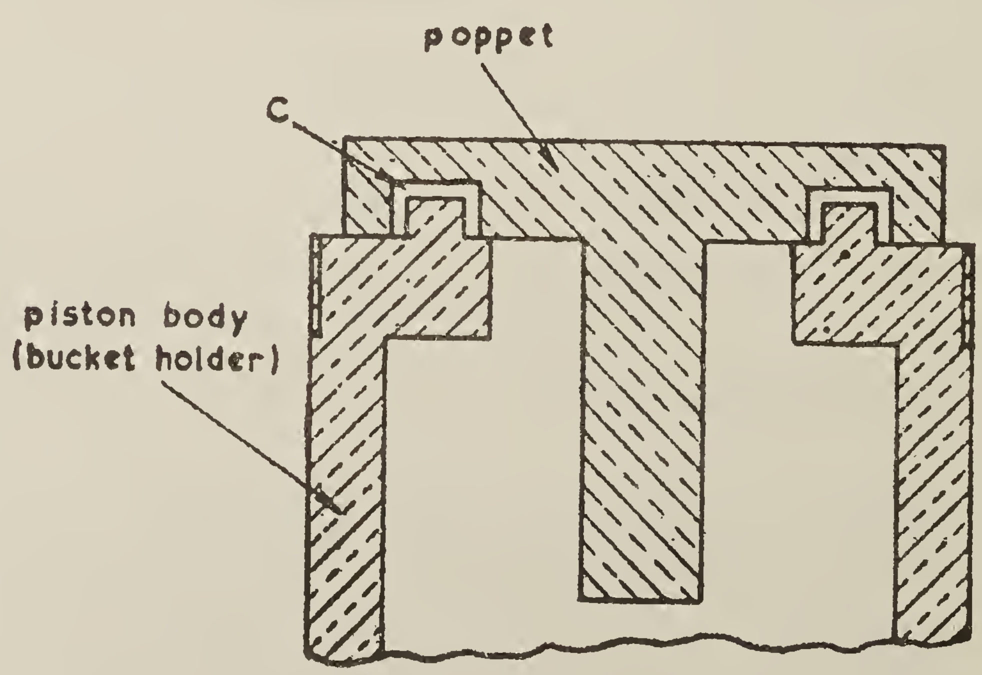

Figure 18. Water cushion for upper valve poppet

8.5 *Disconnection of chain, wearing out of bearings etc.*

Most of the problems connected with the Jalna head arise from lack of lubrication. Any alternative must be capable of running for long periods without the necessity of frequent attention to lubrication. From this point of view, a Watt straight line mechanism (Phelan 1957) is being evaluated (figure 19), which consists of three movable links AB, BC and CD. AB rotates about A, and CD which is part of the handle, about D. A point P in the link BC, located such that $AB/PC = CD/BP$, moves in a path, a part of which is practically a straight line, as the handle oscillates. A plunger rod suspended at P by a pin moves in a straight line without having to take any transverse load. The dimensions of the mechanism have been so chosen that the straight part of the path of P has a length of 124 mm (against the normal stroke of 114 mm (Anon 1976)). The position of P has been slightly displaced from the one which satisfies the equation given above, in order to obtain this stroke length keeping the head compact at the same time. As a result, P deviates a little from a vertical straight line, but never by more than 0·5 mm.

The pins at D, C and P carry loads of the order of 100 kg, and those at A and B, very light loads. The angular velocities involved are very small. Sintered bearings are extensively used for such conditions in motor vehicles. These are journal bearings, made by moulding a mixture of powdered copper and iron under heat and pressure, and filling the pores with oil upto 20% of the total bearing volume. and are known to have a long life without further lubrication in automobiles, electric

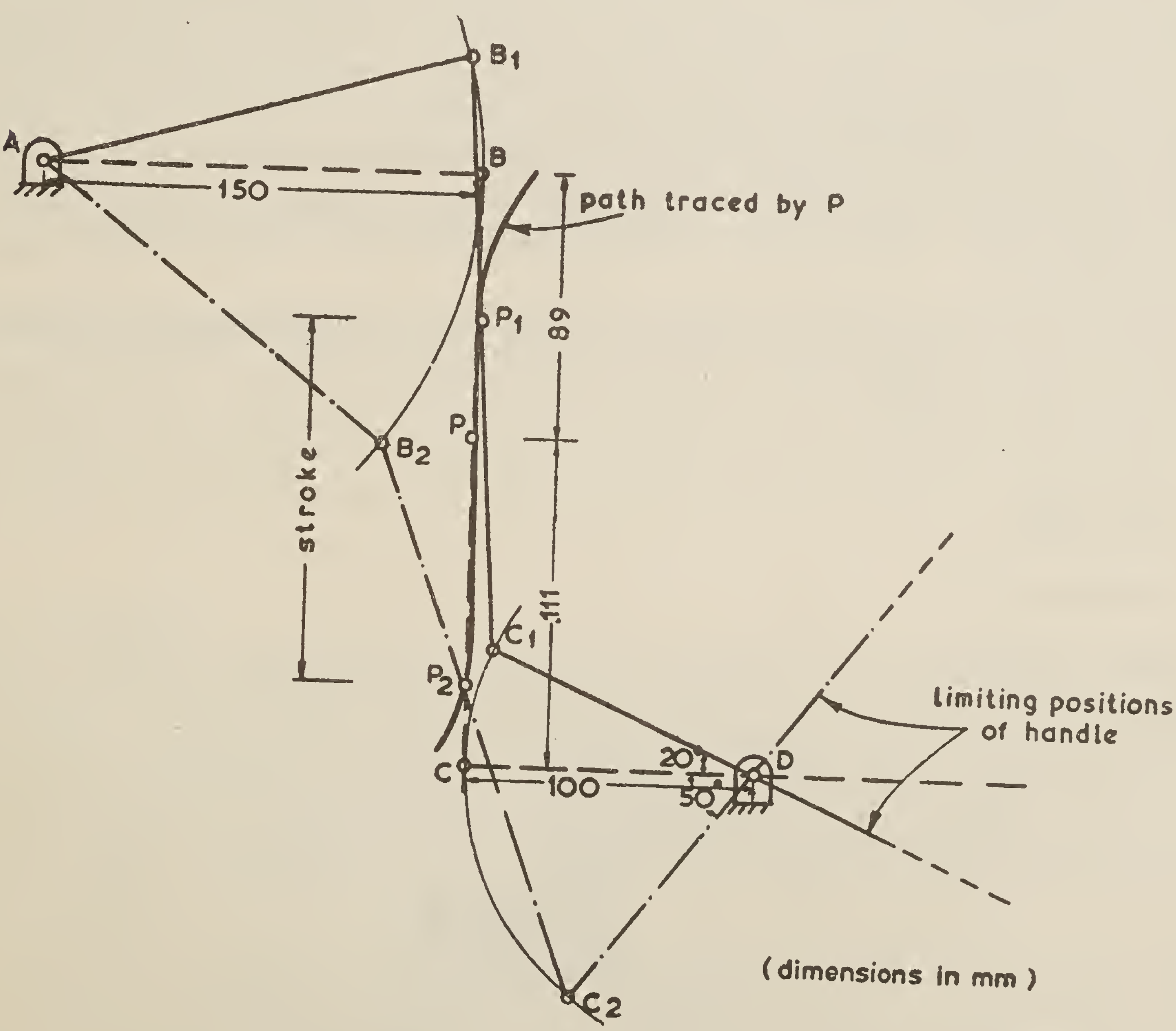

Figure 19. Watt straight line mechanism for handpumps.

shavers etc. (Phelan 1957). The Bangalore pump (Anon 1976) also used sintered bearings, and no measurable wear in them was detected after 1000 hours of testing at 48 strokes/min. A prototype was made and tested at the ASTRA Extension Centre at Ungra, using $12\cdot5 \times 19$ mm bearings at A, B, P and C and a 25×69 mm bearing at D. The bigger bearing at D is to take an eventual unforeseen load, e.g., an adult suspending himself from the end of the handle. While the bearings at A, B and P performed very well, minor problems developed at C and D. A second prototype has been made and installed with the same set of bearings but with redesigned links. This is giving satisfactory performance. Incidentally, with this mechanism a thrust can be transmitted to the piston, so that even when the piston seizes inside the cylinder to some degree, the pump will still work.

8.6 *The upper and lower cages*

The breaking of these cages can be avoided in the conventional way (Phelan 1957) by rounding the corners. The stress flow lines in figure 20 show the effect of rounding in relieving stress concentration.

8.7 *Field trials and dissemination of modifications*

To test the efficacy of the remedial measures, field trials are called for. The Working Group, therefore, proposed to incorporate them in all old pumps in Karnataka which had to be lifted out for repairs, as well as in the new pumps which were going to be installed. To this end, a seminar was held at the Indian Institute of Science (Rama Prasad *et al* 1978) in October 1978, in which about 300 engineers of the Minor Irrigation and Public Health Engineering Department besides the Working Group members participated. An exchange of information on field problems and remedial measures took place. Further, remedial measures have been incorporated in the tender specifications of the Government of Karnataka. Results of the field trials are expected shortly.

In the meantime, the Indian Standards Institution has adopted standard specifications for deepwell handpumps, in which recommendations of this Working Group have been incorporated.

9. Future work

9.1 *Laboratory tests*

Currently, experiments are in progress to determine the frequencies excited in the

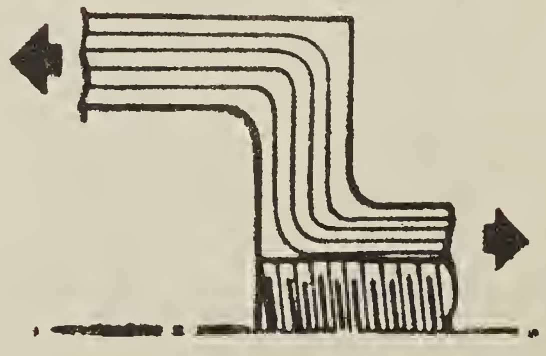

Figure 20. Effect of rounded corners on stress concentration

plunger rod during pump operation and the impact load on the upper valve poppet at the moment of closure. Strain gauges cemented to the piston rod at its top end in the test rig described in § 8.2e are used as pick-up. Future work on the upper valve will be programmed on the basis of these test results.

9.2 *Rural artisan training programme*

In view of the large numbers of handpumps to be dealt with by the central maintenance teams, it is desirable to develop local repair capability as well as to ensure that pumps will work practically all the time. A three-stage training programme has been formulated towards this end. In the first stage, a pilot training camp for about a dozen young artisans of the Ungra region will be conducted, in which instruction will be given on dismantling, repairing and reinstallation of handpumps apart from other aspects. The course material which will consist of demonstration models, charts and pictorial texts will be revised in the light of the feedback from this camp. A second training camp will be conducted to test the revised course material. The third stage consists of a training camp for block-level mechanics from all over the state to enable them in their turn to impart training to artisans in their areas using the course material developed from the earlier camps.

9.3 *Development of an information system*

A good system to monitor the performance of handpumps is necessary to enable (i) the State government to organise its maintenance division, draw up repair schedules, etc., and (ii) the R & D institutions to decide the future course of work. The magnitude of the task of monitoring clearly requires computerisation. Inputs for the system must come from the village and block levels as well as from the MI & PHE Division. The system being developed will be first tried in a group of villages around Bangalore and perfected on the basis of the experience so gained.

9.4 *Reliability monitoring*

While the components of the handpump undergo continued modifications, the overall reliability of the pump will be monitored from time to time, based on the field performance of the pumps as well as laboratory tests on individual components.

10. Conclusions

(i) While a public utility may fail to perform satisfactorily due to many reasons, technical as well as sociological, the present study shows that a detailed technical analysis is vital before attributing the failure of community handpumps to sociological phenomena (e.g. vandalism). The analysis identifies ten modes of failure, the physical factors behind which are vibration, material defects, impact, misalignment and stress concentration.

(ii) These physical factors are also present in the domestic pumps of Europe which are of the same design as our community pumps, but which have performed satisfactorily there. The difference in performance must be attributed to the orders of

magnitude difference between the severity of conditions of operation. In the former case the stresses are light because the water table is high and a pump serves just 4 or 5 people's needs while in the latter, much higher lifts are required and each pump serves some 300 people. In India itself, handpumps in high water table regions, e.g., the cities of Madras and Calcutta, have performed much more reliably than the deep-well handpumps. This highlights the need for careful examination when designs are imported from elsewhere.

(iii) Even when the analysis and experimental results give clear indications, dissemination of the solutions is a difficult and slow process, which must be continuously pursued and monitored to produce results.

(iv) Maintenance of the increasing number of handpumps is going to be very expensive unless their reliability (or MTBF) is increased. The solutions suggested here, together with others being evaluated, indicate that it is possible to increase the MTBF substantially. A ten-fold increase in MTBF is necessary if the current maintenance capability of Karnataka is to keep the pumps serving the entire rural population working.

The author is deeply indebted to Professor A K N Reddy for his invaluable help at all stages of the work. The Karnataka State Council for Science and Technology has funded the project. Thanks are due to Shri M A Sethu Rao, Shri N V Krishna, Dr J Gururaja, Dr S Biswas, Dr U Shrinivasa, Shri A Sathyanarayana Swamy, Shri H N Manjunath and Shri Nagendra Nath for various aspects of the study. The extremely helpful cooperation extended by Shri B Subbaiah, Chief Engineer, Shri T Krishna, Executive Engineer and other officers of the Minor Irrigation and Public Health Engineering Department of the Government of Karnataka is gratefully acknowledged.

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A study on bullock carts. Part 1. Engineering analysis of the two-wheel bullock cart design

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Abstract. An engineering analysis of the design of two-wheel bullock carts has been carried out with the aid of a mathematical model. Non-dimensional expressions for the pull and the neck load have been developed. In the first instance, the cart is assumed to be cruising at constant velocity on a terrain with the effective coefficient of rolling friction varying over a wide range (0·001 to 0·5) and the gradient varying between + 0·2 to − 0·2. Subsequently, the effect of inertia force due to an acceleration parallel to the ground is studied. In the light of this analysis, two modifications to the design of the cart have been proposed and the relative merits of the current designs and the proposed designs are discussed.

Keywords. Bullock carts; design; force analysis; performance; terrain; frictional resistance.

1. Introduction

There are over thirteen million animal-drawn carts in India, most of which are two-wheel carts drawn by one or two bullocks or buffaloes. The design of the conventional cart with two large steel-rimmed wooden wheels has been evolved empirically by the village artisans over the centuries. These carts ply on unprepared terrains in predominantly rural areas and prepared terrains (metalled/tarred/concrete roads) in and around urban areas. To overcome the damage caused by these carts to prepared terrains, some of the two-wheeled carts have been fitted with steel axles and pneumatic wheels. The diameter of the pneumatic wheels is obviously smaller than the diameter of steel-rimmed wooden wheels of conventional carts. No data is available on the effect of a smaller wheel on the performance of the cart.

Recently, the basic mechanics of a two-wheel cart drawn by one or more animals has been analysed (Yajnik 1976). This analysis has been confined to a cart cruising on a level horizontal road. It has been observed that the optimum resultant pull* P_R/W_L (where $P_R=(P^2+W_R^2)^{1/2}$) is virtually insensitive to variations of μ over the range of 0·1 to 0·5 and of h/c over the range of 0·03 to 0·6. What is required, however, is a more comprehensive analysis which also includes the study of the effects of gradient of the terrain, variations in the horizontal and vertical disposition of the centroid of the loaded cart, size of the wheels, etc., on the design and performance of the cart. A comprehensive engineering analysis of the two-wheel bullock cart design aimed at highlighting the weak features in the conventional

*A list of symbols appears at the end of the paper.

design and identifying the areas where design improvements are most effective has, therefore, been carried out. The results of this analysis are presented in this part of the paper.*

2. Force analysis

2.1 *Basic assumptions*

The forces acting on a two-wheel bullock cart are shown in figure 1. In the mathematical model, the cart is assumed to move with uniform acceleration a_c in the direction AC. The dynamic effects due to interaction between the wheel and the terrain and due to locomotion of the bullock(s) are neglected.

The forces at the wheel-ground interface have been studied (Clark 1971; van Eldik Thieme 1971) through constant velocity rolling experiments on pneumatic tyres. No driving or braking torque was applied to the tyres in these experiments. Under large loads, the pneumatic tyre rolling on a hard surface deforms significantly. The relatively large normal stress distribution in the longitudinal direction is non-uniform over the contact length. Consequently, the total normal force R_D acts at a distance e from the normal passing through the wheel axis (figure 2). In addition to the normal stresses, there is a shear stress distribution over the contact region. The resultant shear force F' is a longitudinal force acting in the direction opposite to the direction of motion of the wheel (figure 2). The ratio F'/R_D or μ_g is the coefficient of rolling friction arising from wheel-ground interaction, i.e. ground resistance. When a steel-rimmed wooden wheel rolls on a deformable terrain, e.g. mud road, the terrain deforms while the wheel deformation is negligibly small. The forces at the wheel-ground interface may be considered to be very similar to those that exist in the case of a deformable pneumatic tyre rolling on a hard terrain (figure 2).

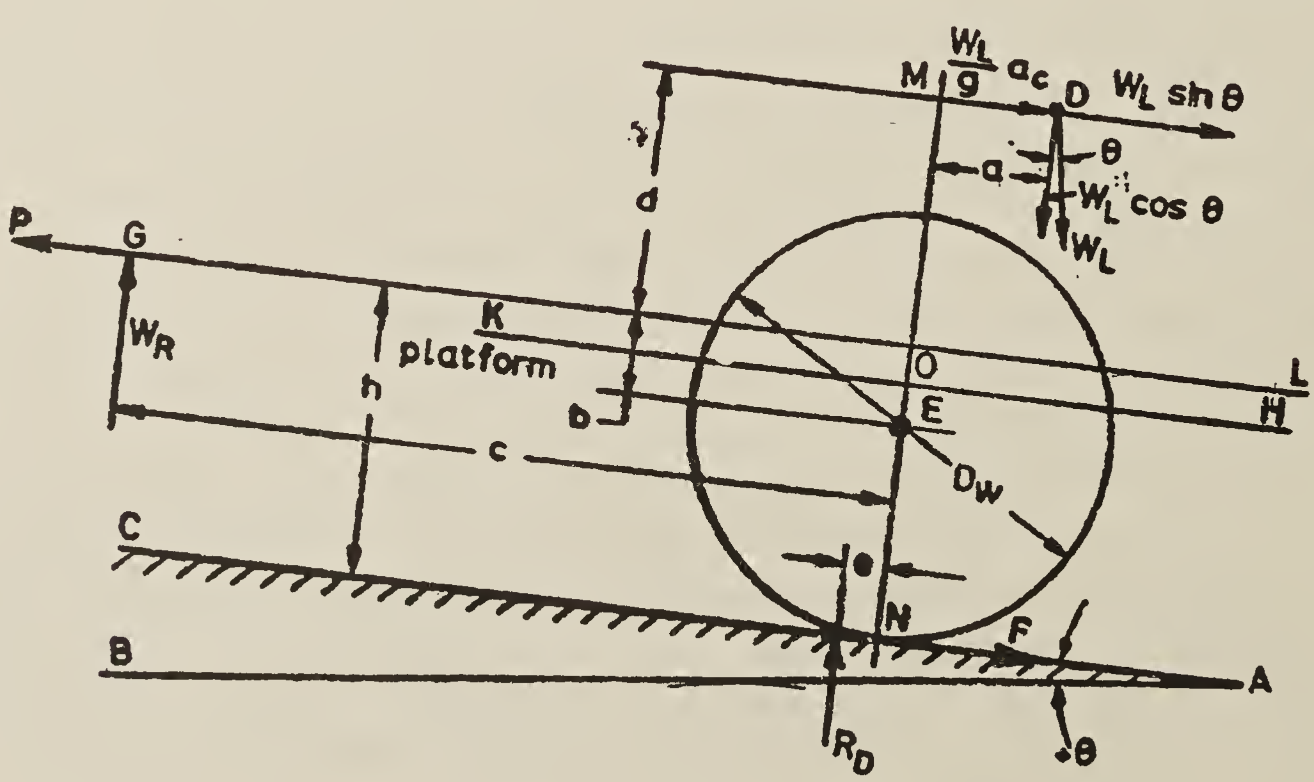

Figure 1. Forces on the bullock cart

*A brief preliminary report of the salient results was presented earlier (Prasanna Rao & Raghavan 1976).

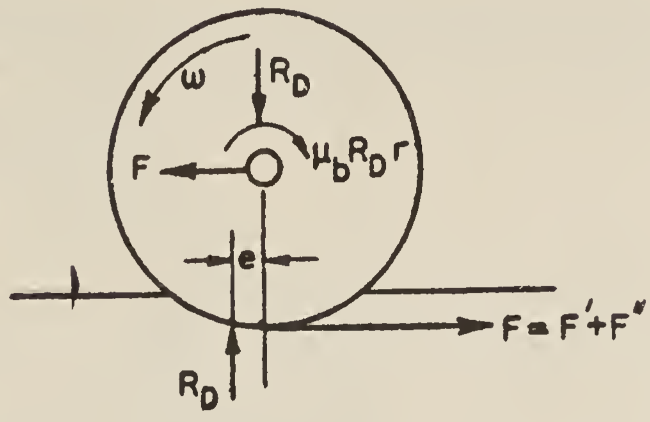

Figure 2. Forces on the wheels

The yoke of a bullock cart generally rests on the neck(s) of the bullock(s) over a region just in front of the hump(s) of the bullock(s). The bullock pushes the yoke as it moves forward. The region of contact, i.e. the contact area, between the yoke and the neck of the bullock may be expected to vary as the bullock moves forward pushing the yoke.

In the present analysis, the frictional force between the neck(s) of the bullock(s) and the yoke is ignored. The force exerted by the bullock(s) on the yoke at time t is resolved into components: pull P and neck load W_R, parallel and normal to the ground respectively. It is assumed that the location of the point of application of the force exerted by the bullock(s) on the yoke with respect to the ground is a constant, i.e., h and c are constants. The inclination of the platform surface, KH to the ground depends on the height h, the wheel diameter D_w, and the level of the platform surface from the ground. It is assumed that KH makes the same angle to the ground under all conditions of operation, i.e., on all terrains. The cart and the load on the cart are assumed to be symmetrical with respect to a plane normal to the wheel axis and located midway between the wheels. The forces exerted by the bullock(s) are also assumed to be symmetrical with respect to this vertical plane so that in the force analysis only the forces in this plane need be considered.

The coefficient of friction of the wheel bearings is μ_b, while the coefficient of friction due to the ground resistance only is μ_g.

2.2 *Effective resisting force*

A free body diagram of the wheel assembly is given in figure 2. From this diagram the effective resisting force F is

$$F' + F'' = [\mu_g + \mu_b\,(r/0.5\ D_w)]\ R_D = \mu\ R_D, \tag{1}$$

so the effective coefficient of rolling friction μ is given by

$$[\mu_g + \mu_b\,(r/0{\cdot}5\ D_w)]. \tag{2}$$

2.3 *Expressions for pull and neck load*

In figure 3 is shown the free body diagram for the yoke-platform-axle assembly. From equilibrium considerations (figures 1 and 3)

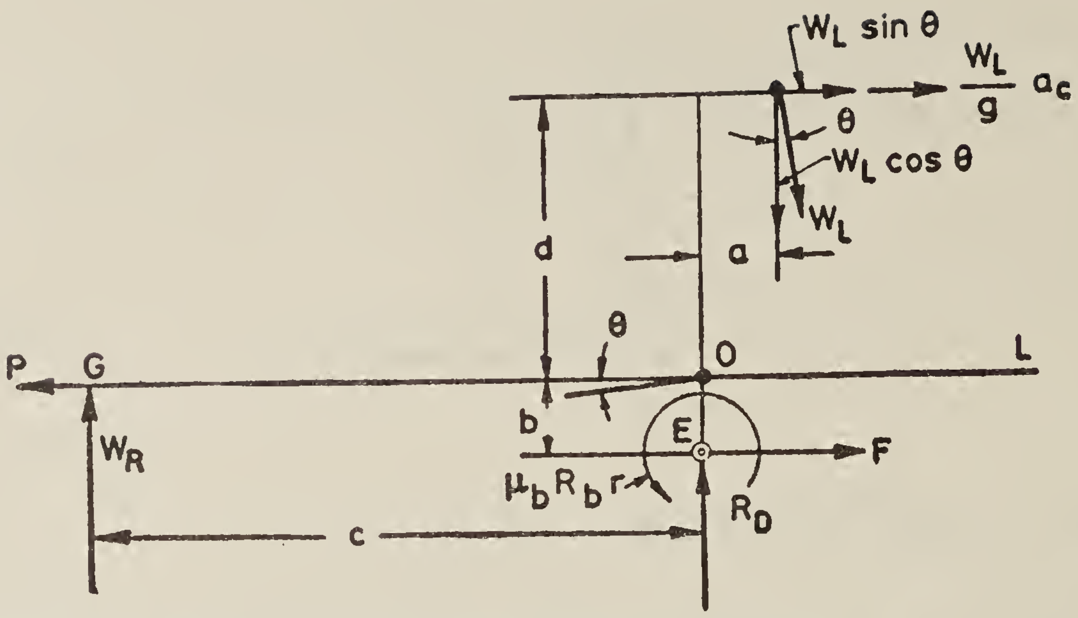

Figure 3. Forces on the yoke-platform-axle assembly

$$P - F - W_L \sin\theta - (W_L/g)\, a_c = 0, \tag{3}$$

$$W_L \cos\theta - W_R - R_D = 0. \tag{4}$$

Taking moments of all forces about the centre line of the axle E,

$$Pb - W_R\, c - W_L \cos\theta\, a - W_L \sin\theta\, (b+d) - (W_L/g)\, a_c\, (b+d) + \mu_b R_D\, r = 0, \tag{5}$$

$$F = \mu\, R_D = \mu\, (W_L \cos\theta - W_R). \tag{6}$$

Solving these equations for P, R_D and W_R and expressing all quantities in the non-dimensional form, we get

$$P/W_L = \mu\, [\cos\theta - (W_R/W_L)] + \sin\theta + a_c/g, \tag{7}$$

$$R_D/W_L = \cos\theta - W_R/W_L, \tag{8}$$

$$W_R/W_L = \frac{\cos\theta\, [\mu(b/c) - (a/c) + (\mu_b\, r/c)] - (a_c/g)\,(d/c) - (d/c)\sin\theta}{1 + (\mu\, b/c) + (\mu_b\, r/c)}. \tag{9a}$$

The term $(\mu_b\, r/c)$ in the denominator can be neglected as it is very small compared to 1. ($(\mu_b\, r/c)$ is about 0·003 for μ_b of 0·2, axle diameter of 10 cm and c of 380 cm). Also as the maximum contribution to the neck load (W_R/W_L) due to the bearing friction torque is less than 0·003 the term $(\mu_b\, r/c)$ in the numerator can also be neglected. So the final expression for the neck load is

$$W_R/W_L = \frac{\cos\theta\, [(\mu\, b/c) - (a/c)] - (d/c)\, [\sin\theta + (a_c/g)]}{[1 + \mu\, (b/c)]}. \tag{9}$$

This equation shows that the neck load can be reduced by designing the cart such that b is quite small. Also, when b is zero, the neck load is independent of μ.

As $\qquad b = h - 0{\cdot}5 D_w, \qquad (10)$

b can be quite small only if $D_w \approx 2h$. This implies that the wheel diameter should be large and close to twice the height of the neck of the bullock(s).

2.4 *Variables and design parameters*

The sensitivity of the various variables is studied and the performance of the cart under various operating conditions (terrain and load) is analysed. In the first instance, to simplify analysis, the cart is assumed to cruise at uniform velocity i.e. $a_c = 0$. The expressions for the performance variables P/W_L and W_R/W_L, for a cart cruising at uniform velocity are from equations (7) and (9).

$$P/W_L = \mu\,(\cos\theta - W_R/W_L) + \sin\theta, \tag{11}$$

$$W_R/W_L = \{\cos\theta\,[\mu(b/c) - (a/c)] - (d/c)\sin\theta\}/[1 + \mu(b/c)], \tag{12}$$

where θ is positive if the gradient of the terrain is uphill, negative if the gradient is downhill.

2.4a. *Range of variables and parameters* In this analysis the diameter of the wheels D_w is varied over a wide range: 30·5 cm (12 in.) to 183 cm (72 in.). The size of the bullocks h enters indirectly into the analysis through b (equation (10)). b is varied over a wide range by keeping h constant at a typical value of 101·5 cm (40 in.) and varying D_w over a wide range. As all dimensions, b, a and d, are non-dimensionalised by dividing them by c, c can be kept constant at a typical value of 380 cm (150 in.). As P and W_R are non-dimensionalised by expressing them in terms of W_L, this analysis is valid for all loads on the cart.

From equation (2) it is seen that the contribution of the bearing friction to μ is only a small fraction $(2r/D_w)$ of the bearing friction μ_b. For example, with an axle of diameter of 50 mm (2 in.) the contribution of bearing friction to μ is only 3 %, 8 % and 16 % of μ_b for wheel diameters of 193 cm (72 in.), 61 cm (24 in.) and 30·5 cm (12 in.) respectively.

μ_b which varies with the type of bearing and the mode of lubrication lies in the range 0·001 to 0·2 (Shigley 1972). The coefficient of friction μ_g is estimated to be in the range 0·01 to 0·5 (Marks 1951). For a limited analysis of the bearing friction and wheel diameter on the performance of the cart, μ_b is assumed to be equal to μ_g and they are varied over the range 0·001 to 0·2. For all other analysis, μ is varied over the range 0·001 to 0·5. The horizontal shift a of the centre of gravity (CG) of the laden cart with respect to the vertical MN through the axle centre (figure 1) is varied over the range +30·5 (12 in.) to —30·5 cm (—12 in.). The normal distance d between the CG of the laden cart and the line of action of the pull LG is varied over a wide range: 0 to 91 cm (36 in.).

3. Performance of the two-wheel bullock cart

All computations have been carried out using a digital computer. Typical results of this analysis are presented in figures 4 and 5.

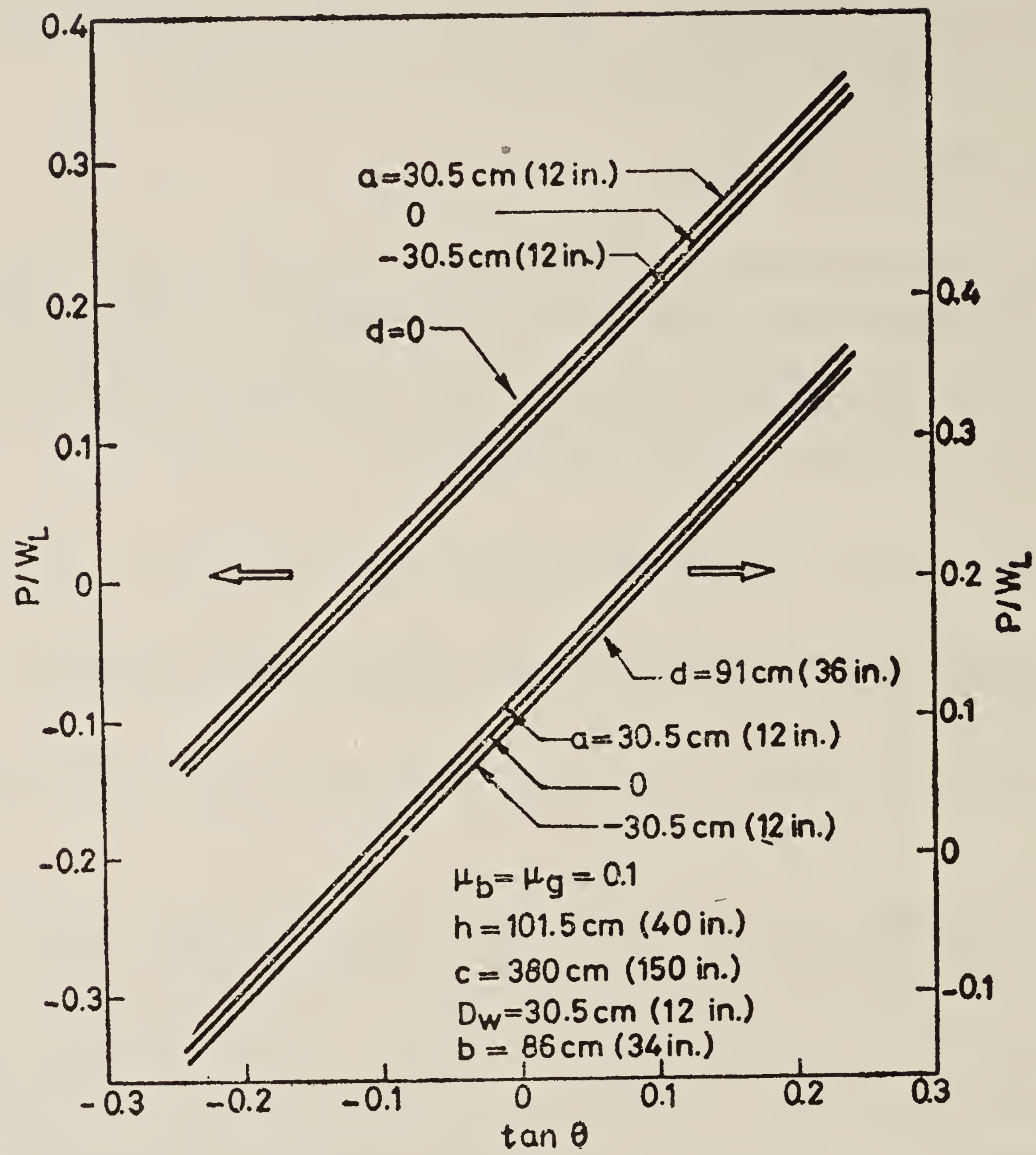

Figure 4a. Effect of the gradient of the terrain on pull P/W_L. Wheel diameter = 30·5 cm (12 in.)

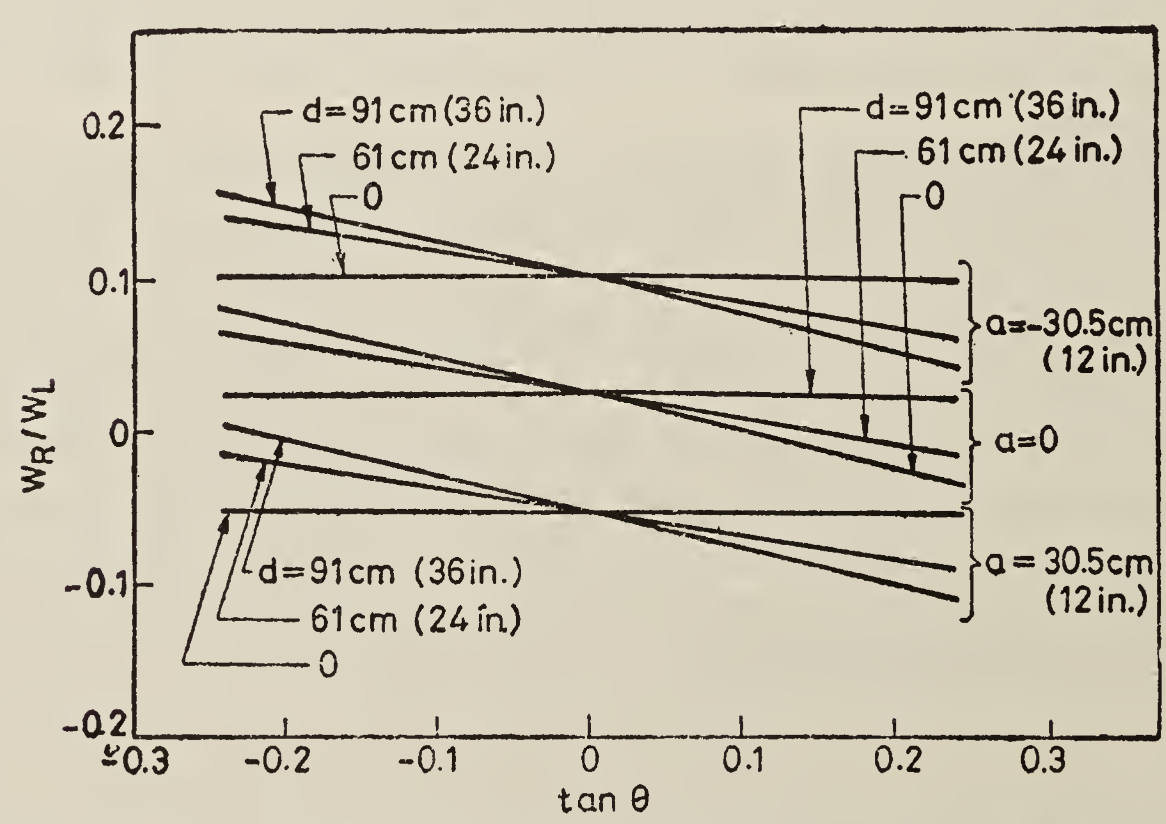

Figure 4b. Effect of the gradient of the terrain on neck load W_R/W_L. Wheel diameter = 30·5 cm (12 in.)

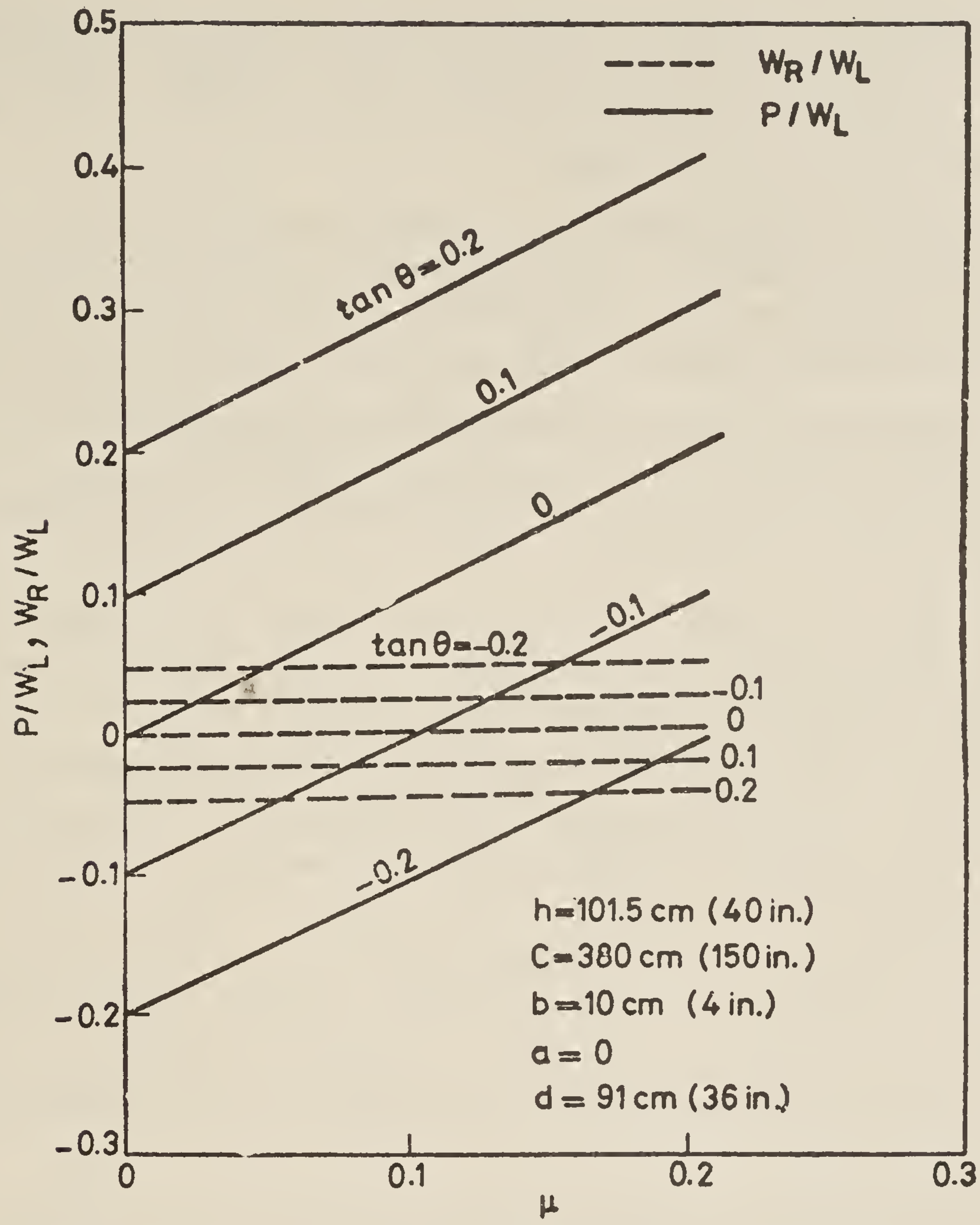

Figure 5. Effect of μ and tan θ of the terrain on the performance. Wheel diameter = 183 cm (72 in.)

3.1 *Effect of gradient on the performance*

The effect of the gradient of the terrain on the performance of carts fitted with wheels of diameter 30·5 cm (12 in.), 61 cm (24 in.) and 183 cm (72 in.) operating on a terrain with μ_g=0·1 has been studied. In this study, μ_b is also kept constant at 0·1 i.e., $\mu_b = \mu_g = 0 \cdot 1$. The other operational variables *d* and *a* defining the CG of the laden cart are varied to study their effects. Typical results are presented in figure 4—for cart with D_w=30·5 cm (12 in.).

3.1a *Pull* This study shows that the magnitude of pull P/W_L is significantly affected by the gradient of the terrain. A change in the gradient of ±0·1 results in a change of P/W_L of about ±0·1 (figure 4a). In a cart with balanced load (a=0) on a downhill gradient of 0·11, the pull is zero. This means that, at higher downhill gradients, the yoke of the cart loses contact with the hump on the neck of the bullocks and the bullocks have to arch their necks upwards to apply a backward force to keep the cart stable. Or, a brake should be provided and applied to prevent the cart from becoming unstable.

On a ground with constant gradient, P/W_L is rather insensitive to changes in the magnitude of *d*. For example at tan θ=0·2, P/W_L varies only by about 2%, when *d* varies from 0 to 91 cm (36 in.). It is also seen that the shift (parallel to the ground)

of CG of the laden cart by $\pm 30{\cdot}5$ cm (± 12 in.) from the balanced position ($a=0$) causes only an insignificant change in P/W_L. For example, on all gradients, a forward shift of a by 30·5 cm decreases P/W_L by only 0·008; a backward shift by 30·5 cm increases P/W_L by only 0·009.

This analysis shows that on any terrain, whatever be the diameter of the wheels, variations in the laden weight of the cart (W_L) and in the location of the CG of the cart (defined by d and a) have an insignificant effect on the magnitude of the pull P/W_L to be exerted by the bullocks. If at all loads, i.e. at all d values, the minimum neck load requirement for negotiating the maximum uphill gradient expected is met by a suitable initial variation of a, the pull P/W_L required for operation on a given terrain with constant μ_g and gradient, is independent of the wheel diameter.

3.1b *Neck load* On a level road the neck load in a cart with balanced load ($a=0$) is a function of μ and b/c only. Thus an increase in b, i.e. decrease in wheel diameter, D_w with h constant, or increase in bullock neck height, h with D_w constant, increases the neck load almost linearly. For instance on a level ground with balanced load and $\mu_g = \mu_b = 0{\cdot}1$, the neck load is 0·026, 0·020, and 0·003 for carts with wheel diameters of 30·5 cm (12 in.), 61 cm (24 in.) and 183 cm (72 in.) respectively.

The effect of variation of the gradient of the terrain on the neck load is about the same for all wheel diameters. For instance, at $d=91$ cm (36 in.) the change in the neck load due to a variation of the gradient from $-0{\cdot}2$ to $+0{\cdot}2$ is about 0·092 for all wheel diameters (note that $\mu_g = \mu_b = 0{\cdot}1$). In order to minimise the neck load the cart should be designed to have at full load as small a value of d as possible. This aspect is discussed in § 4.

Under identical conditions of operation—same d, tan θ, μ_g, μ_b and a—the effect of change in a on the neck load, is about the same for all wheel diameters. Also, the neck load is quite sensitive to the horizontal shift of CG of the cart, i.e. change in a from the balanced position ($a=0$). For example, a rearward shift of CG by 30·5 cm (12 in.) from the balanced position results in a decrease of 0·079 in the neck load.

From this study, it is seen that the neck load can be kept at the minimum value required for effective traction by changing a by an amount dependent on the gradient of the terrain and the magnitude of d. This calls for a cart design by which when the cart is in motion there is a provision to manually shift the position of the CG of part of the cargo or the whole cargo to the desired extent. Such an arrangement, however, may decrease the simplicity and increase the cost of the cart.

3.2 *Effect of frictional resistance of the terrain on the performance*

In the previous section, the effect of gradient of the terrain on the performance was studied at constant ground friction and bearing friction i.e. $\mu_g = \mu_b = 0{\cdot}1$. In this section, the performance of the cart with wheel diameters of 30·5 cm (12 in.), 61 cm (24 in.) and 183 cm (72 in.) is studied when it moves over a terrain with effective coefficient of rolling friction μ varying over the range of 0·001 to 0·5; this study has been made for level terrain and terrains with gradients of $\pm 0{\cdot}1$ and $\pm 0{\cdot}2$. It is assumed that the load on the cart is maximum and balanced i.e. $a=0$ and d is say 91 cm. The results of this study are presented in figure 5 for the cart with wheels of diameter of 183 cm (72 in.). A study of this figure and similarly figures for wheel diameters

of 30·5 cm (12 in.) and 61 cm (24 in.) shows that in all cases the pull P/W_L increases almost linearly with μ. Further, under identical conditions of operation, i.e., same terrain gradient and μ, the magnitude of the pull is about the same for all wheel diameters.

In the case of carts with large wheels, the effect of variation of μ on the neck load is not significant on level terrain or sloping ground. For example, for a cart with wheels of diameter 183 cm (72 in.) on level ground, W_R/W_L is only 0 006 and 0·014 at μ of 0·2 and 0·5 respectively. However, the variation of the neck load with μ is significant in the case of carts with smaller wheels. For example, on a level ground with μ of 0·5, the neck load for a cart with a wheel diameter of 61 cm (24 in.) is about 550% higher than that for a cart with 183 cm (72 in.) diameter wheels.

The variation in the neck load for a cart with 183 cm (72 in.) diameter wheels plying on a terrain with gradient varying between +0·2 to —0·2 and with μ varying between 0·001 to 0·5 is 0·106. The corresponding value for the variation in the neck load for a cart with 61 cm (24 in.) diameter wheels is 0·174. Thus, from neck load considerations, one should prefer larger diameter wheels for the cart (the maximum diameter of the wheel is limited to 2 h). This is particularly so in the case of carts plying in rural areas where the maximum μ is likely to be as high as 0·5.

4. Design modification for improved performance

The analysis presented in the previous sections show that the diameter of the wheel D_w — in terms of the design parameters b and the level of platform from the ground, h — and the variable d, has a profound influence on the neck load of the bullocks. In this analysis, the level of the platform from the ground was taken to be constant for all

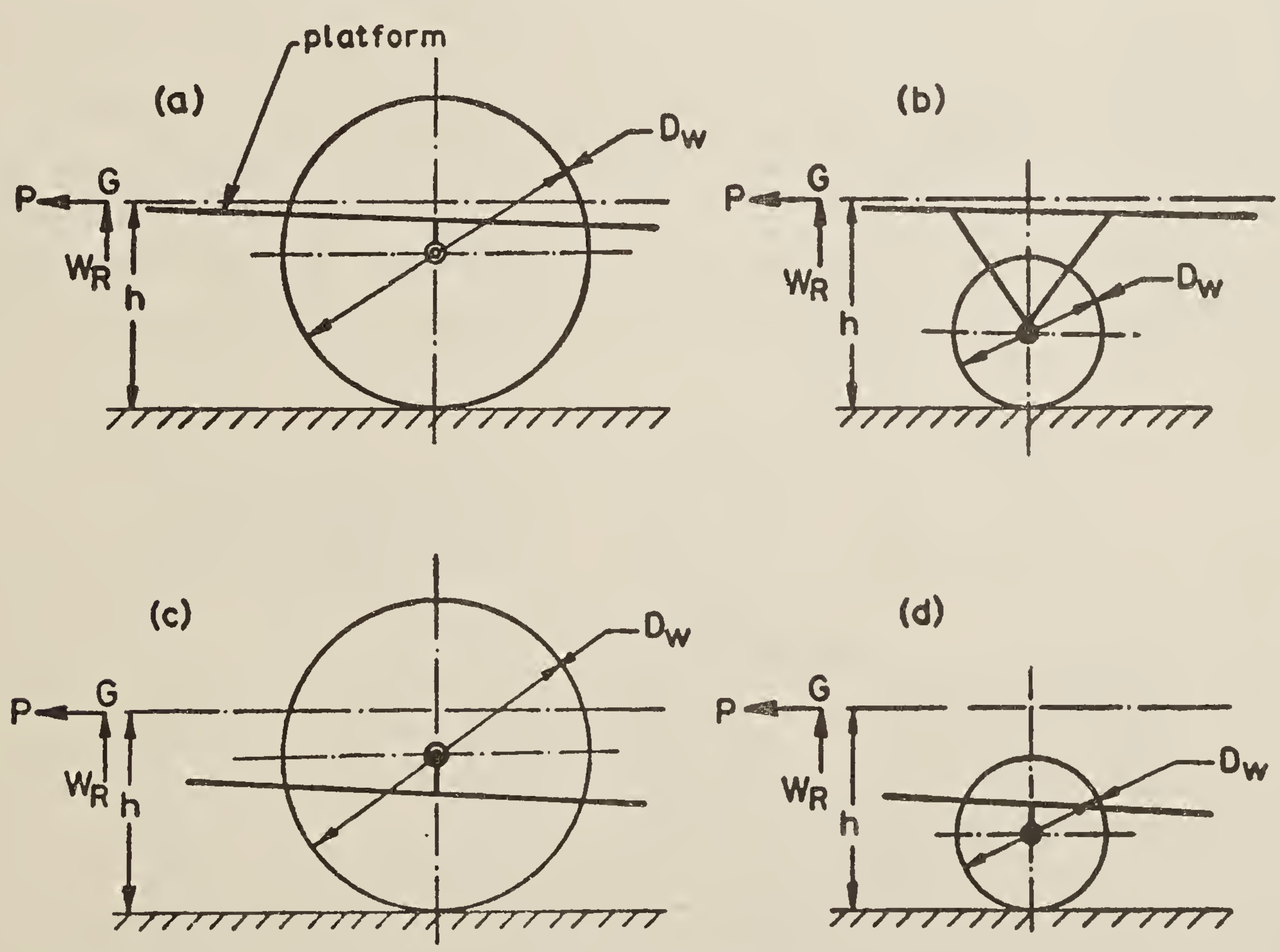

Figure 6.7 Carts of type A, type B and type C designs. (a) Type A design with large wheel (platform just above the axle). (b) Type B design with small wheel (elevated platform above the axle). (c) Type C design with large wheel (platform underslung below the axle). (d) Type A design with small wheel (platform just above the axle).

wheel diameters and set equal to that provided in 183 cm (72 in.) diameter wheel cart of current design (type A design in figure 6a). As mentioned already, this also represents the current practice in the design of a large number of carts with pneumatic smaller wheels (type B design in figure 6b). Two design modifications are proposed —one for the large wheel cart (type C design in figure 6c) and the other for the small wheel cart (type A design in figure 6d), for reducing the neck load and enhancing the stability of the loaded cart. A comparative study of the performance of these four designs is presented below.

4.1 *Smaller wheel cart of type A design*

It is proposed to lower the platform of the smaller wheel cart to the same level above the axle as in the cart with large wheels (183 cm diameter wheel) (figure 6d) to effect a significant decrease in the magnitude of d corresponding particularly to full load on the cart. Such a decrease in d enhances the stability and produces a considerable decrease in the neck load. For instance, lowering the platform of a 61 cm (24 in.) diameter wheel cart to the same level above the axle as in a 183 cm (72 in.) diameter wheel cart (type A design) brings down the CG of the fully loaded cart from say 91 cm (36 in.) to 30 cm (12 in.). The effect of this change in design on the neck load is shown in figure 7 for terrains with μ varying from 0 to 0·2 and the gradient varying between $\pm$ 0·2. As a minimum neck load, $(W_R/W_L)_{\min}$, is necessary for effective traction particularly on terrains with low friction and high uphill gradient, it is assumed in the present study that this minimum value of neck load is provided in 61 cm (24 in.) diameter wheel carts of both type A and type B designs. The neck load in the cart of modified design (type A design) varies from $(W_R/W_L)_{\min}$ to $[(W_R/W_L)_{\min} + 0{\cdot}067]$ as μ varies from 0 to 0·2 and tan θ varies from $+0{\cdot}2$ to $-0{\cdot}2$. The corresponding variation in the neck load in the cart of type B design, i.e. platform elevated to the same level as in 183 cm (72 in.) diameter wheel cart, is 0·128. Thus, in the cart of modified design (type A design), the maximum neck load is considerably lower and the neck load variation over the minimum is lowered by 48 %.

In figure 8 the neck load variation in 183 cm (72 in.) diameter wheel conventional cart (type A design) and 61 cm (24 in.) diameter wheel cart of modified design (type A design) is compared when operated in terrains with μ varying over the range 0 to

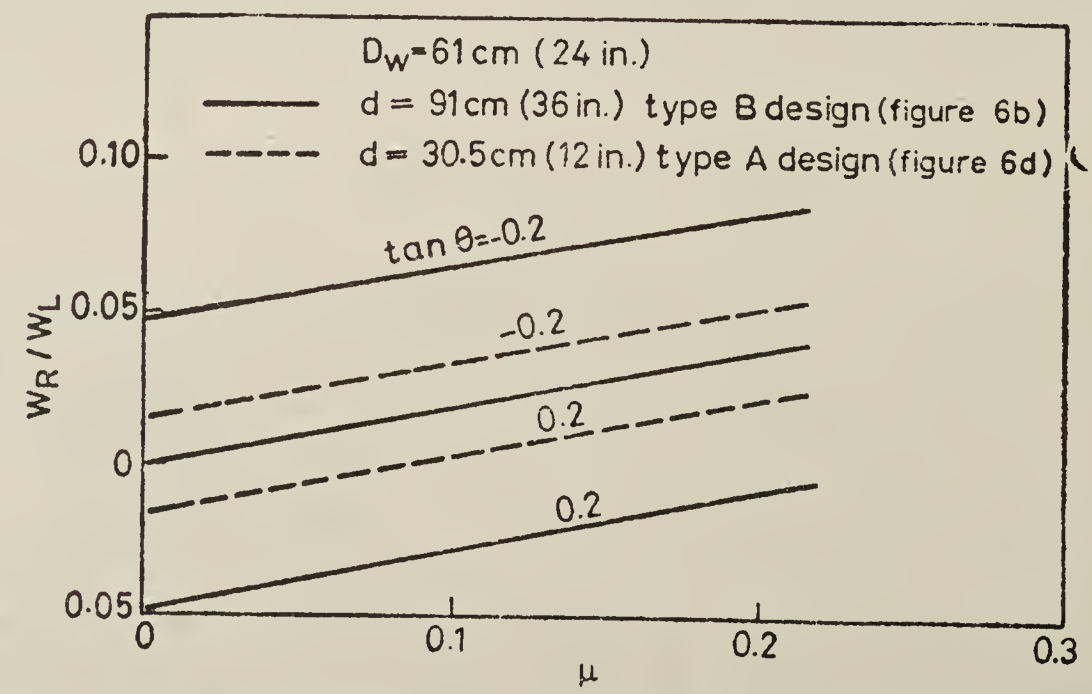

Figure 7. Neck load in smaller wheel cart of type A and type B designs.

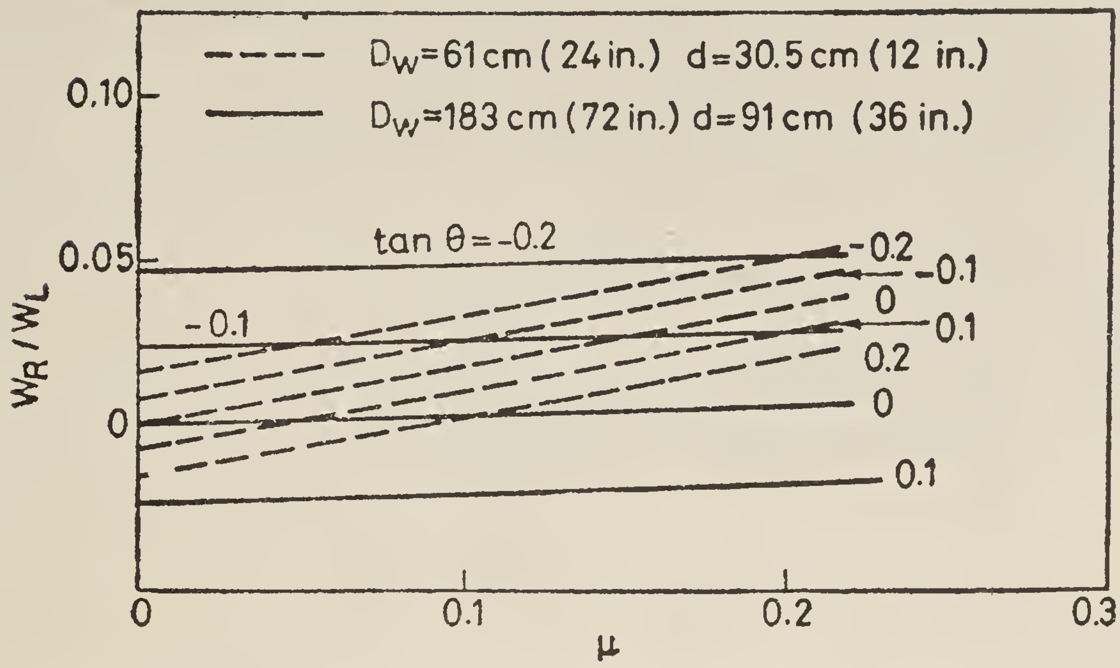

Figure 8. Effect of wheel diameter on the neck load in carts of type A design.

0·2 and gradient varying between + 0·2 to —0·2. It is seen that the magnitude and variation of neck load in the smaller wheel cart of modified design are considerably lower. The figures for neck load variations under these conditions for the smaller wheel cart of modified design and the larger wheel cart of conventional design are 0·067 and 0·099 respectively. That is, the neck load variation in the smaller wheel cart of modified design is 32% lower. A further study shows that on a terrain with μ varying between 0 to 0·5 and gradient varying between +0·2 to —0·2, the variation in the neck load for the smaller wheel and larger wheel carts are 0·103 and 0·106 respectively. Thus, in type A design carts from neck load and stability considerations smaller wheel carts are more attractive than the larger wheel carts.*

4.2 *Large wheel cart of type C design*

It has been shown earlier in equations (10) and (12) that if b is zero i.e. $D_w=2h$, the neck load is independent of the effective coefficient of friction μ. For a cart with h=100 cm (40 in.) the wheels have to be 200 cm (80 in.) in diameter for the neck load to be independent of μ. In the case of cart with 183 cm (72 in.) diameter wheels and h=100 cm, the neck load variation on a terrain of constant gradient is only 0·014 for a variation of μ over a large range of 0 to 0·5. However, in the large wheel cart of type A design with the platform just above the axle, the magnitude of d at full load is high particularly in the case of low density cargo. As seen from the earlier discussion, the larger the magnitude of d, the greater the effect of the gradient on the neck load. The magnitude of d at full load can be reduced in this cart by lowering the platform to a suitable level below the axle level (type C design in figure 6c). In figure 9, the neck load variation with μ and gradient (tan θ) for identical cart load (W_L) is given for two types of carts having wheels of the same diameter of 183 cm (72 in.). The two types of carts compared here are: conventional cart of type A design with platform above axle (d=91 cm (36 in.)) and type C cart (modified design) with underslung platform (d=35·5 cm (14 in.)). In the latter cart, the clearance between the platform and the ground is about 38 cm (15 in.). It is seen that in the cart of type C design plying on a terrain with μ varying between 0 and 0·2 and the gradient varying over the range

*It is assumed here that the magnitude of μ on a given terrain is unaffected by the diameter of the wheel.

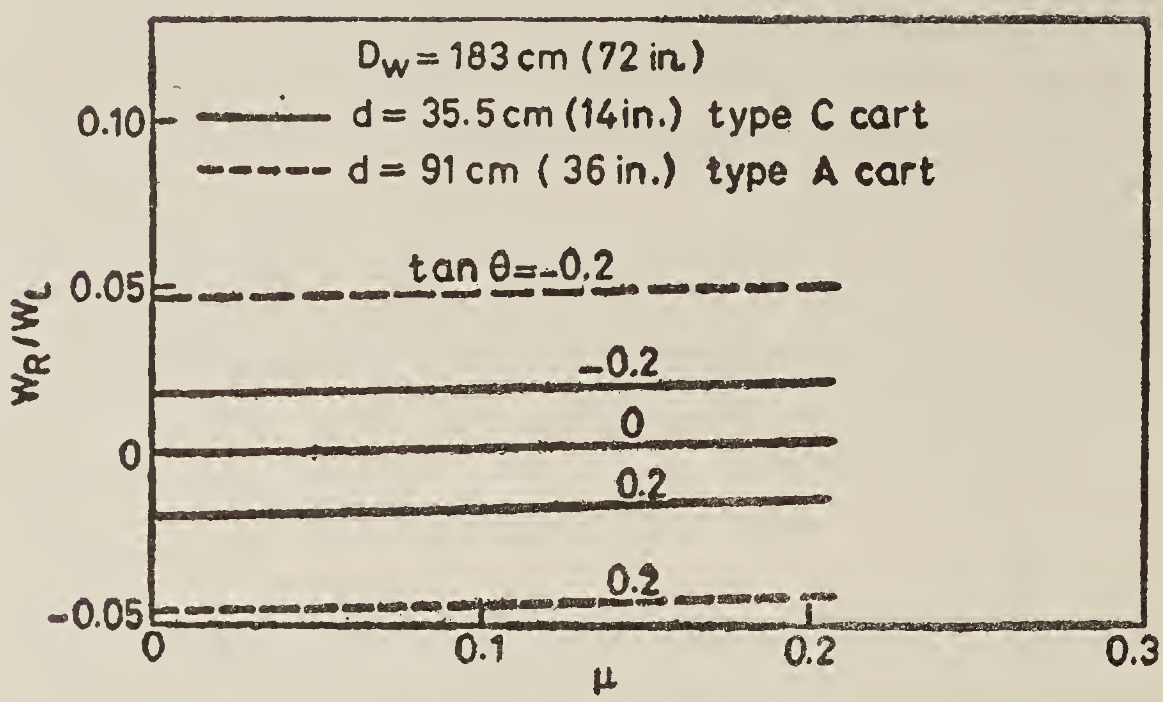

Figure 9. Neckload in 183 cm (72 in.) diameter wheel cart of type A and type C designs.

+0·2 to —0·2, the neck load variation is only 0·041 as compared to 0·099 in the cart of type A design. Thus there is about 60% reduction in the neck load variation in the cart of type C design. Further, the cart of type C design has enhanced stability and lower maximum neck load.

A comparative study of the performance of a 183 cm (72 in.) diameter wheel cart of type C design (d=35·5 cm (14 in.)) and a 61 cm (24 in.) diameter wheel cart of type A design (d=30·5 cm (12 in.)) plying with identical cart load (W_L) over a terrain with μ varying over a range: 0 to 0·5 and gradient varying between + 0·2 to — 0·2 shows that the neck load variation under these conditions in the former cart is about 50% lower. This study shows that from stability and minimum neck load considerations the large wheel cart of type C design is the most attractive.

5. Wheel bearings

It can be seen from equation (2) that the contribution of bearing friction to the effective coefficient of rolling friction, μ is (r/0·5 D_w) times the coefficient of bearing friction μ_b. For example with an axle of 5 cm diameter, the contribution of bearing friction to μ is only 3% and 8% of μ_b in carts with wheels of diameter 183 cm (72 in.) and 61 cm (24 in.) respectively. Further, as these carts operate at very low speeds, little advantage is gained by the use of costly anti-friction bearings (ball and roller bearings) in these carts. Sleeve bearings lubricated with suitable grease or viscous oil are satisfactory from both cart and performance considerations. However, these bearings should be provided with suitable thrust faces to take up the thrust loads arising from lateral motions of the loaded platform and the wheels.

6. Inertia loads

The analysis presented thus far is for carts cruising at constant velocity on terrains with varying μ and gradient. Here, the effect of acceleration a_c parallel to the ground, on the pull and the neck load is considered. Under all conditions of operation, the

inertia force due to acceleration a_c (equation (9)) reduces the neck load. As there has to be a minimum neck load for effective traction, the inertia force due to acceleration a_c increases the magnitude of variation of the neck load on the bullocks. It also increases the maximum neck load. By decreasing d (equation (9)) under fully loaded conditions, the neck load component due to inertia force can be reduced. Smaller wheel carts of type A design and large wheel carts of type C design have significantly lower values of d at full load. Hence, in these carts the neck load component due to inertia force is considerably lower than in other cart designs.

From equation (7), it is seen that the component of pull due to inertia force is directly proportional to the acceleration a_c.

7. Brakes

From the analysis presented above, it is noted that on downhill gradients greater than 0·1, the pull required is negative for all terrains with μ less than about 0·1. Under these conditions of operation, some form of brake for the cart is essential to maintain stability of the cart and to avoid discomfort to the bullocks.

8. Conclusions

An engineering analysis of the design of two-wheel bullock carts has been carried out with the aid of a mathematical model. Non-dimensional expressions for the pull and the neck load have been developed. In the first instance, the cart is assumed to be cruising at constant velocity on a terrain with the effective coefficient of rolling friction μ varying over a wide range: 0·001 to 0·5 and the gradient varying between + 0·2 to — 0·2. Subsequently, the effect of inertia force due to an acceleration a_c parallel to the ground, is studied. In the light of this analysis, two modifications to the design of the cart have been proposed and the relative merits of the current designs and the proposed designs are discussed. The broad conclusions of this study are:

(i) The pull P/W_L is highly sensitive to the gradient of the terrain. Also it is a linear function of μ and a_c.

(ii) On any terrain, variations in the laden weight (W_L) of the cart and in the location of the CG of the laden cart has only an insignificant effect on the pull.

(iii) Under identical loading (W_L, d and a constant), the effect of variation of the gradient of the terrain with constant μ on the neck load is about the same for all wheel diameters,

(iv) The neck load is quite sensitive to the horizontal (parallel to the terrain) shift a of the CG of the laden cart from the balanced position $a = 0$. Under identical conditions of operation—the same gradient, μ, d and a—the effect of change in a on the neck load is about the same for all wheel diameters.

(v) For minimum neck load variation due to changes in μ one should prefer larger diameter wheels for the cart with the maximum diameter of the wheels limited to $2h$.

For the neck load variation due to the expected gradient change to be a minimum particularly at full load, d should be as small as possible.

(vi) Two new designs for the cart are proposed—one for the cart with larger wheels

(type C design) and the other for the cart with smaller wheels (type A design). A comparison of neck load variation in these carts with those in the conventional carts i.e., cart with large wheels (type A design) and the smaller wheel cart with elevated platform (type B design) shows that from neck load considerations the proposed type C cart design with relatively large size wheels (e.g. 183 cm (72 in.) diameter wheels) is most attractive. Also in type A design carts the smaller wheel carts (proposed design) are more attractive than the larger wheel conventional carts (in this analysis μ is assumed to be independent of the wheel diameter).

(vii) For the wheels, sleeve bearings lubricated intermittently with suitable grease or viscous oil are satisfactory from both cost and performance considerations. However these bearings call for a machined axle. Thrust faces should be provided in these bearings to take up thrust loads.

(viii) The inertia loads due to acceleration a_c are relatively small in these slow speed vehicles. The neck load component due to this inertia force is significantly low in the proposed cart designs—smaller wheel cart of type A design and the large wheel cart of type C design.

(ix) Some form of braking should be provided to ensure stability of the cart and to minimise discomfort to the bullocks while plying on terrains with down hill gradient and very low coefficient of rolling friction.

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List of symbols

- a — shift of centre of gravity of the cart D with respect to the normal to the ground passing through the point of contact N and wheel centre E; cm (in.)
- a_c — acceleration of cart in the direction of motion; cm/s^2 (in./s^2)
- b — normal distance between the wheel centre and the line of action of pull P; cm (in.)
- c — normal distance between the wheel centre and the line of action of the neck load W_R; cm (in.)
- d — normal distance between the centre of gravity of the cart D, and the line of action of pull P; cm (in.)
- d' — $b + d$
- D_w — wheel diameter; cm (in.)
- e — eccentricity of line of action of reaction R_D; cm (in.)
- F' — frictional force due to ground resistance; kgf (lb)
- F'' — force at the wheel periphery to overcome bearing friction torque; kgf (lb)
- F — $(F' + F'')$, effective resisting force; kgf (lb)

g acceleration due to gravity; cm/s^2 (in./s^2)
h height of the point of application G of the resultant force due to the bullocks, from the ground; cm (in.)
P pull or component of the force exerted by the bullock(s) parallel to the ground; kgf (lb)
$2r$ diameter of wheel axle; cm (in.)
R_D normal reaction at the ground acting at an eccentricity e; kgf (lb)
W_L total weight of the laden bullock cart; kgf (lb)
W_R neck load or component of the force exerted by the bullock(s) normal to the ground
μ_b coefficient of friction of the bearing
μ_g coefficient of rolling friction due to the ground resistance
μ effective coefficient of rolling friction
θ inclination of the ground to the true horizontal (degrees)
$\tan\theta$ gradient.

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A study on bullock carts. Part 2. Experimental study of forces in a bullock cart

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Abstract. A strain gauge load cell with separate bridges for measurement of the pull and the bending moment in the plane containing the net neck load and pull was developed and fixed in the longitudinal member of an experimental cart. A cart fitted first with pneumatic wheels and then with steel-rimmed wooden wheels was tested on three terrains—tar road, mud road and grassy terrain. Pull vs time and moment vs time records were obtained in each test and analysed.

It is found that the bullocks pull the cart rather discontinuously at the low velocities at which these carts normally operate. On the tar road and the grassy terrain, the mean static coefficient of friction is significantly higher for the cart with steel-rimmed wooden wheels. The dynamic frictional resistance of the terrain for the cart with steel-rimmed wooden wheels is lower than for the cart with pneumatic wheels so long as the wheels do not dig or sink into the terrain. The fluctuation in the neck load is lower in the cart fitted with pneumatic wheels. Also, the ground-induced low-amplitude high-frequency vibratory load content in the neck load is lower in the cart with pneumatic wheels.

Keywords. Bullock cart; experimental cart; measurement; strain gauge load cell; calibration; frictional resistance.

1. Introduction

The net load capacity of conventional and two-wheel pneumatic (Dunlop ADV tyres) tyre carts are claimed to be about 1 tonne and 2·5 tonnes respectively (Anon 1977). From steady static tests some comparative data have been obtained on the effective rolling friction μ (combined ground friction and bearing friction) offered in cases of steel-rimmed wheels and pneumatic tyres on a few typical terrains. The data given in table 1 (Marks 1951) show that μ for pneumatic tyres on concrete road is slightly more than for steel-rimmed wheels. On other terrains, μ for pneumatic tyres is only 15 to 25% lower. This implies that the draw-bar pull in carts fitted with pneumatic tyres is about 1·6 to 1·75 that of conventional carts if it has to carry 2·5 times the net load carried by conventional carts. No data are available on the effect of carrying such heavier loads on the necks of the bullocks and their life.

In a series of investigations conducted more than three decades ago (Vagh 1944–51) several designs for the steel-rimmed wooden bullock-cart wheel were tested in a cart pulled manually by several persons. A special spring-dynamometer involving the use of a third wheel in front was used to record on a drum recorder the variation of draw-bar pull during the test. The spring-dynamometer-cum-recorder is perhaps

A list of symbols appears at the end of the paper.

Table 1. Data on μ for pneumatic and steel-rimmed wheels (Marks 1951)

Type of Wheel	Load kgf	Surface			
		Concrete	Blue grass sod	Tilled loam	Loose sand
Wheel with steel tyres (diameter 60 to 120 cm; width: 6·3 to 20 cm)	227–682	0·010–0·034	0·065–0·094	0·236–0·468	0·264–0·504
Pneumatic tyres (4–18 to 7·5–36; 9–16; 4 to 6 ply) (tyre pressure: 1·1–2·5 kg/cm^2)	227–682	0·017–0·042	0·050–0·070	0·185–0·401	0·177–0·460

unsuitable for use with bullocks providing the tractive effort. These tests were conducted on concrete, water-bound (WB) Macadam and earth roads. From draw-bar pull and minimum damage to road considerations, it was claimed that the steel-rimmed wooden wheels (conventional design) are satisfactory provided the tyre width is increased from 5 cm to 7·5 cm.

However, no detailed analysis has been reported in the literature on μ and the dynamic effects on the pull and neck loads under actual operating conditions. Hence, in the present study, a two-wheel cart was fitted with a strain gauge load cell specially designed for this purpose. The instrumented cart provided independent records of pull and neck load under actual operating conditions. Details about this instrumented cart and analysis of the results of tests wherein this cart fitted first with pneumatic tyres and then with conventional steel-rimmed wheels was operated on various types of terrains, are presented here.

For an experimental study of the performance of a two-wheel bullock cart fitted with either steel-rimmed wooden wheels or pneumatic wheels and operating on various types of terrains, the forces exerted by the bullocks on the cart have to be measured under actual operating conditions. A load cell is required to measure these forces. An important requirement this load cell has to satisfy is that its introduction into the system should not significantly alter the characteristics of the bullock cart. The load cell and the associated instruments should faithfully record the dynamic variations of these forces i.e., the pull and the neck load, while the cart is in motion. A study of various measuring devices show that a strain gauge load cell fitted in the longitudinal member (figure 1) of the cart is well suited for this purpose.

2. Strain gauge load cell

A load cell located in the longitudinal member of the cart is subjected to the following forces and moments (figure 1)

$$P=P_1+P_2, \tag{1a}$$

$$W_R=W_{R1}+W_{R2}, \tag{1b}$$

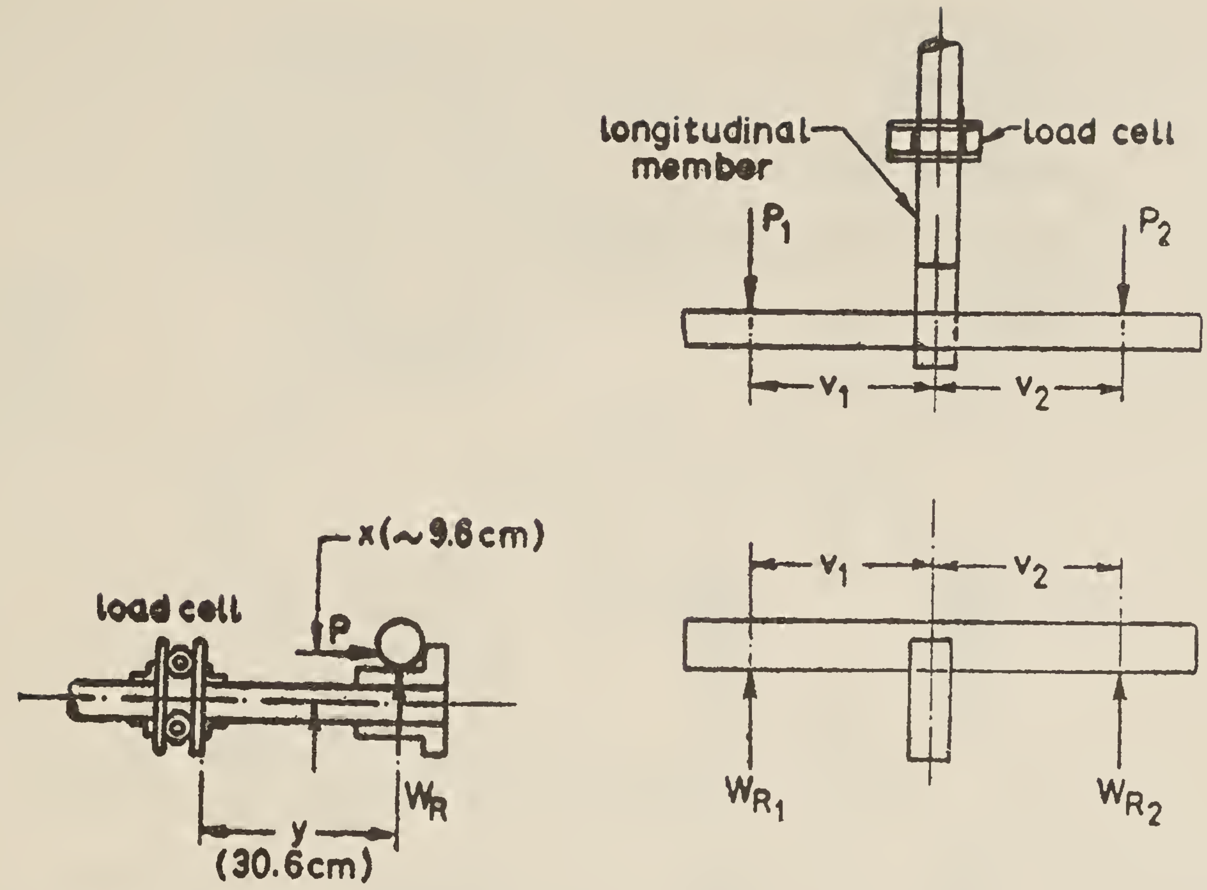

Figure 1. Forces on the yoke of the bullock cart

$$M_{ll} = W_R y - Px, \tag{1c}$$

$$M_{nn} = P_1 v_1 - P_2 v_2, \tag{1d}$$

$$T = W_{R1} v_1 - W_{R2} v_2, \tag{1e}$$

where P_1 and P_2 are the pulls exerted by the two bullocks and W_{R1} and W_{R2} are the corresponding neck loads on the bullocks.

The load cell should satisfy the following important requirements:

(i) it should be capable of measuring at any instant both P and W_R;

(ii) the output of the load cell corresponding to P should be insensitive to the magnitude of the shear force W_R, the bending moments M_{ll} and M_{nn} and torque T;

(iii) the output of the load cell corresponding to the neck load W_R could either indicate directly the neck load or give the neck load indirectly through the bending moment M_{ll}. In the present design it was found convenient to measure M_{ll}. The load cell output indicating this bending moment should be unaffected by the stresses in the load cell due to the axial load P, shear force W_R, bending moment, M_{nn} and torque T.

(iv) The stiffness of the load cell in both longitudinal and transverse directions should preferably be greater than the stiffness of the longitudinal wooden member.

A strain-gauge load cell which satisfies all these requirements is shown in figures 2 and 3. In this load cell, four stainless steel octagonal rings each having 40 mm inside diameter and 3 mm minimum wall thickness, are sandwiched between two 15 mm thick mild steel plates. Bolts (8 mm diameter) and nuts are used to fix these rings to the

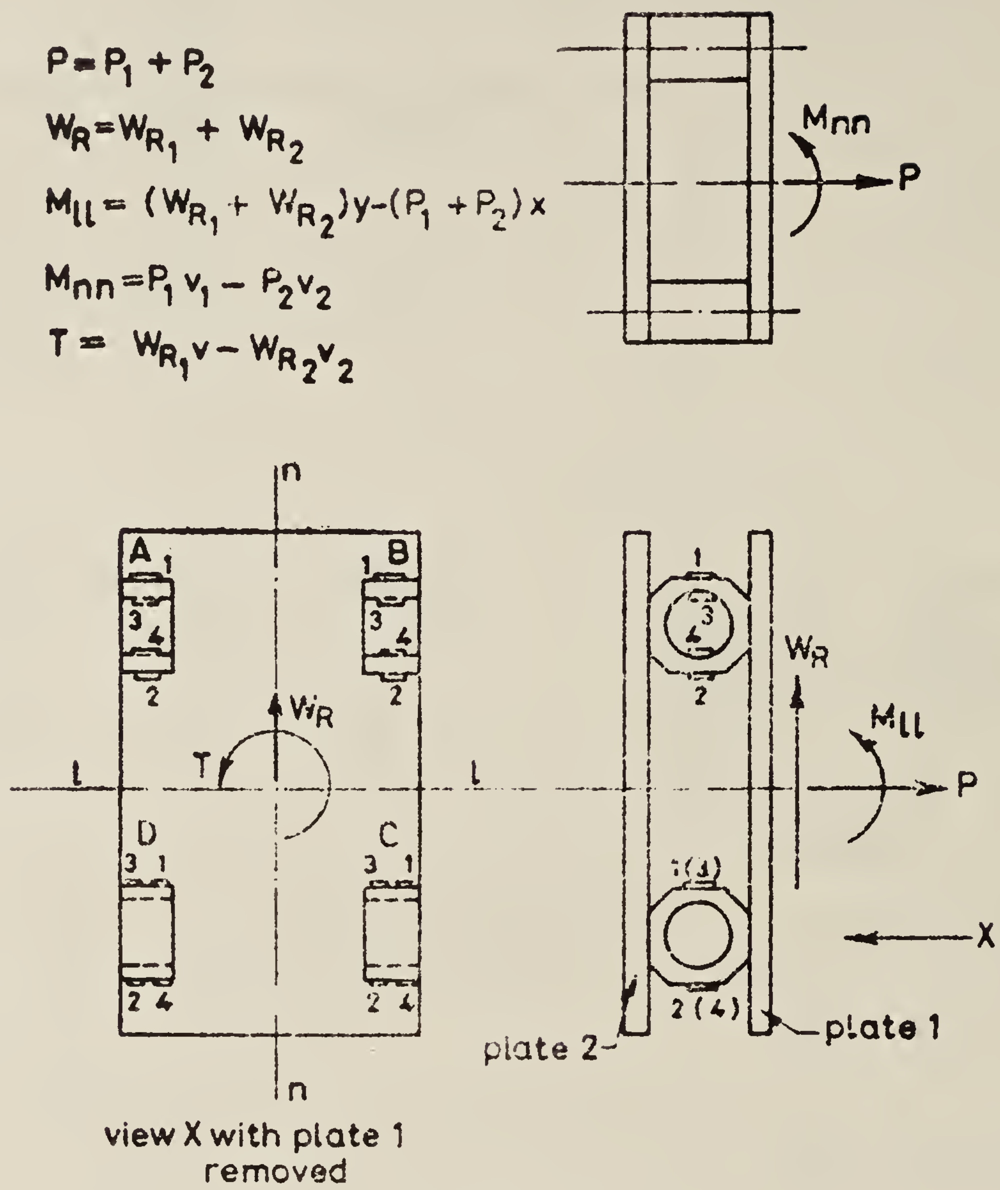

Figure 2. Forces and moments on the load cell

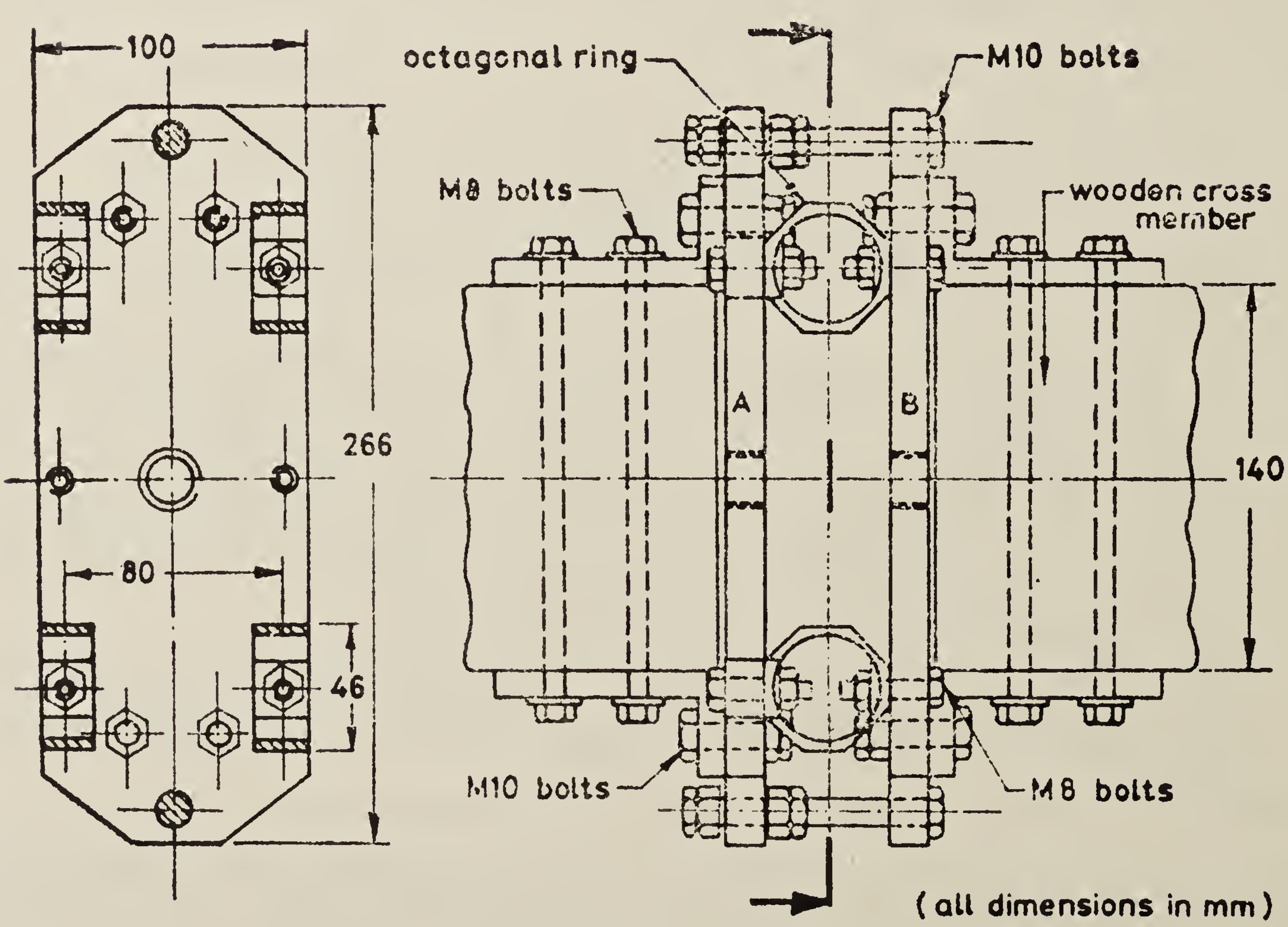

Figure 3. Load cell assembly

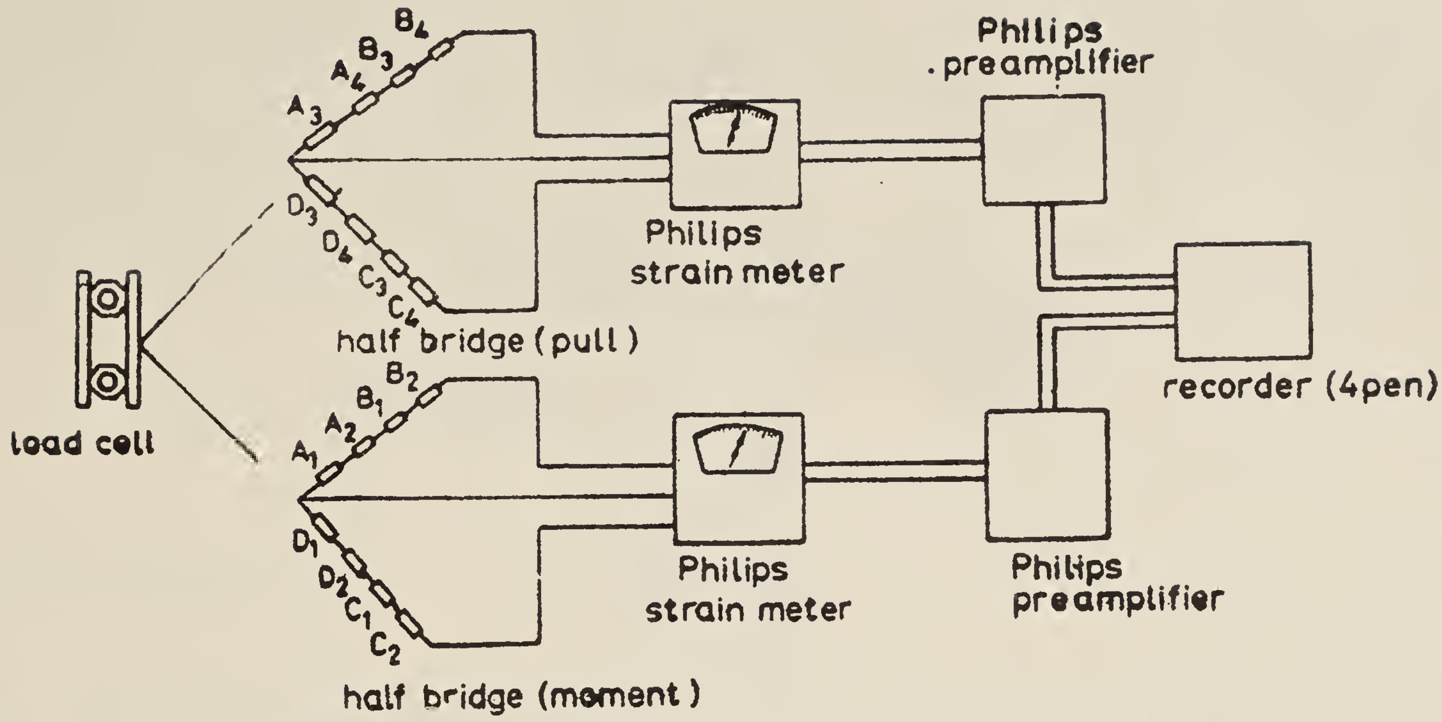

Figure 4. Load cell output recording system

steel plates. Sixteen 120Ω strain gauges (*Satya* gauge type SA-12-STCL, grid length 5 mm) are fixed on these rings as shown in figure 2. These strain gauges are connected as shown in figure 4 to form two half-bridges for measuring directly P and M_{II}. The half bridges are connected to a Kelvin and Hughes four-pen recorder through Phillips strain meters and preamplifiers (figure 4). The excitation voltage (220 V 50 cycles AC) for the strain-measuring system was obtained through a petrol engine-generator set mounted on the platform of the cart (figure 5, plate 1). An automatic voltage regulator was used to obtain steady voltage supply. All measuring instruments and associated equipment were mounted on the platform of the cart (figure 5, plate 1).

Some design details on the load cell are given in figure 3. As may be seen in this figure, stops are provided to prevent the overloading of the load cell. The longitudinal wooden member in the cart is cut at a station about 30 cm from the yoke end and the load cell is fixed between the cut pieces through angles, bolts and nuts (figure 3).

3. Calibration of the load cell

The four octagonal-faced rings with strain gauges fixed on them were individually tested in compression in an universal testing machine for checking the satisfactory performance of the strain gauges. The load cell was then assembled and tested in tension in the universal testing machine. After ensuring satisfactory performance of the load cell the stops were adjusted to limit the maximum axial load to 500 kgf and bending moment to 30 kgfm. The load cell was then fixed as described earlier to the longitudinal member of the cart and instrumented. It was then calibrated for axial load and bending moment.

The set-up used for axial load calibration through dead weights is shown in figure 6 (an additional joint provided in the longitudinal wooden member between the load cell and the wooden platform facilitated this test). The calibration constant for axial load was found to be 1·03 $\mu\epsilon$/kgf. The cross sensitivity i.e., the ratio of the outputs of the bending moment bridge and the axial load bridge, was less than 2%.

Two arrangements shown in figure 7 were used for bending moment calibration through dead weights. In one set-up (figure 7a) vertical loads were applied on the yoke

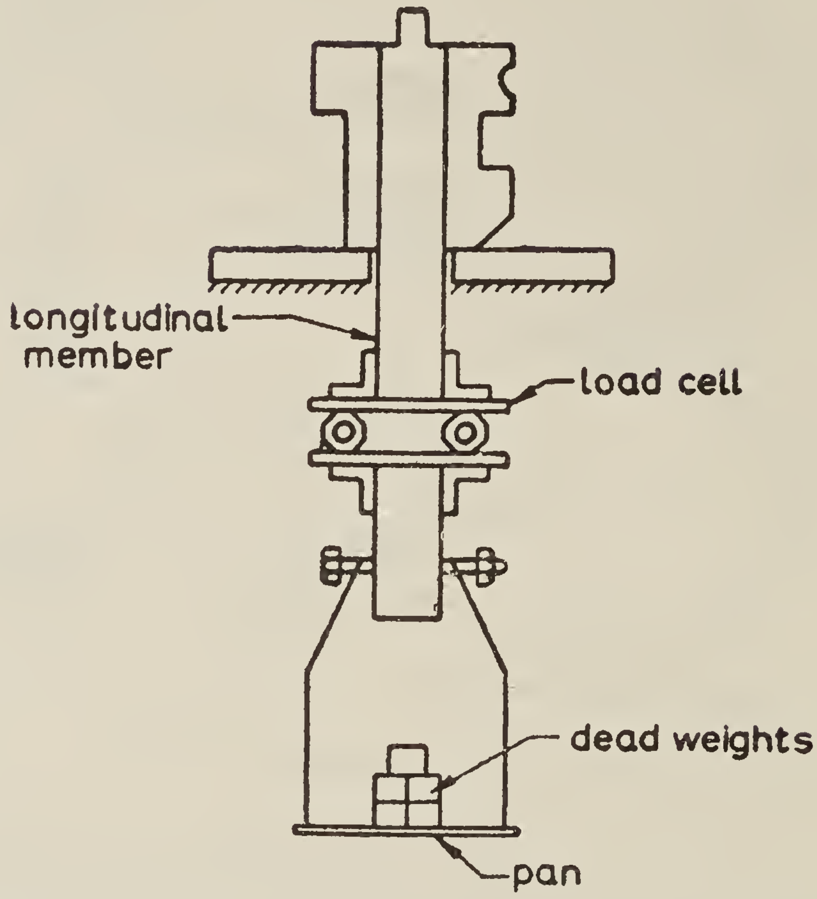

Figure 6. Set-up for axial load calibration using dead weights.

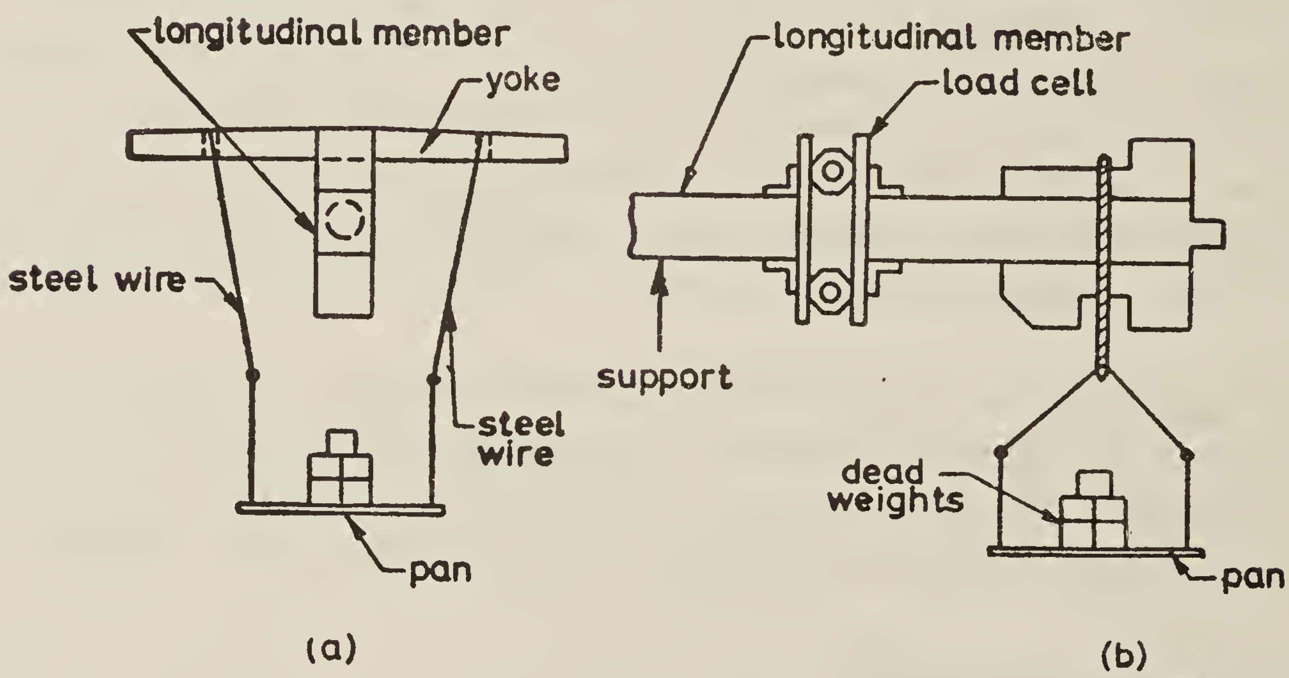

Figure 7. Arrangements for bending moment calibration with simulated load W_R.

at the locations where the yoke rests on the two bullocks. In the other set-up (figure 7b), a vertical load was applied directly to the longitudinal member at the section where the yoke transmits in the actual cart, load to the longitudinal member. Both tests gave the same calibration constant of 3·3 $\mu\epsilon$ per kgf vertical load in the yoke i.e., 9.3 kgcm bending moment per $\mu\epsilon$.

During the actual test, a shunt resistance was used to calibrate the axial load measuring system in terms of pen deflection per unit micro strain on the strain meter. This used along with the calibration constant of the load cell in terms of microstrain per unit axial load i.e., 1·03 $\mu\epsilon$/kgf gave the calibration constant for the axial load measuring system in terms of load per millimeter pen deflection; this calibration constant was about 29·5 kgf/mm deflection of the pen recorder.

In the case of bending moment measuring system, the calibration constant in terms of pen deflection per unit microstrain was found at the commencement of each test by applying a static lateral load on the yoke of the cart. This data used along with

calibration constant from the earlie rcalibration test i.e., 3·3 $\mu\epsilon$/kgf vertical load gave the calibration constant of the bending moment measuring system in terms of kgf per mm pen deflection. About 10 kgf vertical load on the yoke produces 1 mm deflection of the pen of the recorder.

From the measured values of the bending moment M_{ll} and the pull P the corresponding neck load can be determined through equation (1c). Thus

$$W_R = (M_{ll}/y) + (Px/y). \tag{2}$$

4. Test conditions

The experimental cart fitted alternately with conventional steel-rimmed wheels and pneumatic wheels were tested on three types of terrains located around the Internal Combustion Engineering building of the Indian Institute of Science, Bangalore. The specifications of the experimental cart and details about the pneumatic and wooden wheels are given in table 2. The three types of terrains are:

(i) tar road: two strips hereafter termed as tar road 1 and tar road 2;
(ii) dry mud road: a stretch of road with a thin layer of mud over compacted stone jelly and sand;
(iii) unprepared grassy (green grass) terrain.

Table 2. Specification of the experimental cart

1. *General:*
   Platform size: 218 cm × 82·5 cm (86 in. × 32·5 in.)
   Platform height from the ground: 106 cm (41·8 in.)
   Distance between the wheel centre and the neck of the bullocks, c=283 cm (111·5 in.)
   Height of the neck of the bullocks from the ground h=100 cm (40 in.)
   Centre distance between the bullocks (necks): 107 cm (42 in.)

2. *Steel-rimmed wooden wheels*
   Diameter D_w: 150 cm (60 in.)
   Width : 5 cm (2 in.)
   Thickness of steel belt: 1·5 cm (0·6 in.)
   No. of spokes: 12
   Axle diameter: 3·2 cm (1·25 in.)
   Weight of each wheel: 86·2 kgf (190 lb.)
   Centre distance between the wooden wheels on the cart: 126 cm (49·5 in.)

3. *Pneumatic wheels*
   Specification: S75-6·00-16, 6 ply rating
   Type: New Deluxe Champion of M/s Firestone
   Outside diameter of inflated wheels: 70 cm (27·5 in.)
   Tread width: 11 cm (4·3 in.); Tread partially worn
   Weight of pneumatic wheels with axle and tie rod assembly: 71·2 kgf (157 lb.)
   Centre distance between the wheels: 128 cm (50·5 in.)
   Tyre pressure: 1·4 and 2·1 kgf/cm² (20 and 30 psig)

5. Test procedure

Besides the strain measuring equipment and the engine-generator set, cast iron weights were placed in the cart in suitable positions to provide the required load on the cart. The static neck load on the two bullocks with the cart driver in position was in the range of 40 to 56 kgf.

At the commencement of each test, the platform of the experimental cart (without the bullocks) was made horizontal by supporting the longitudinal member at a point between the load cell and the platform so that there was virtually no load on the load cell. The engine-generator set was then started and the strain measuring bridges were activated and allowed to warm up. After balancing the bridges for capacitance and resistance unbalance, both the bridges were calibrated as described above. The support to the longitudinal member was removed before the bullocks were tied to the cart. The cart was then moved to the starting point marked on each terrain. The recorder was switched on just before the cart driver drove the cart over the test length of the terrain. The pens recorded the pull and bending moment M_H throughout the test. The recorder was switched off at the end of the test. The average velocity of the cart was determined with a stop-watch by clocking the time taken by the cart to cover the test length. The cart was then turned round for operation over the same stretch in the reverse direction. During this test also, pull and bending moment records were obtained and the average speed of the cart was also determined.

6. Analysis of test data

The experimental cart fitted with pneumatic wheels was run with tyre pressure of 1·4 (20 psi) and 2·1 kgf/cm² (30 psi) on each chosen terrain both in the forward and reverse directions. The pneumatic wheels were then removed to fit the cart with conventional steel-rimmed wooden wheels. The experimental cart with conventional steel-rimmed wheels was then tested over the same terrains the pneumatic wheel cart was tested. Pull and bending moment records were obtained in all cases. A typical set of pull vs time and moment vs time records is given in figure 8.

A study of the pull vs time records shows that the bullocks pull the cart rather discontinuously. The waviness in the pull vs time record is ascribed to the discontinuous motion of the bullocks as they walk along pulling the cart. As may be

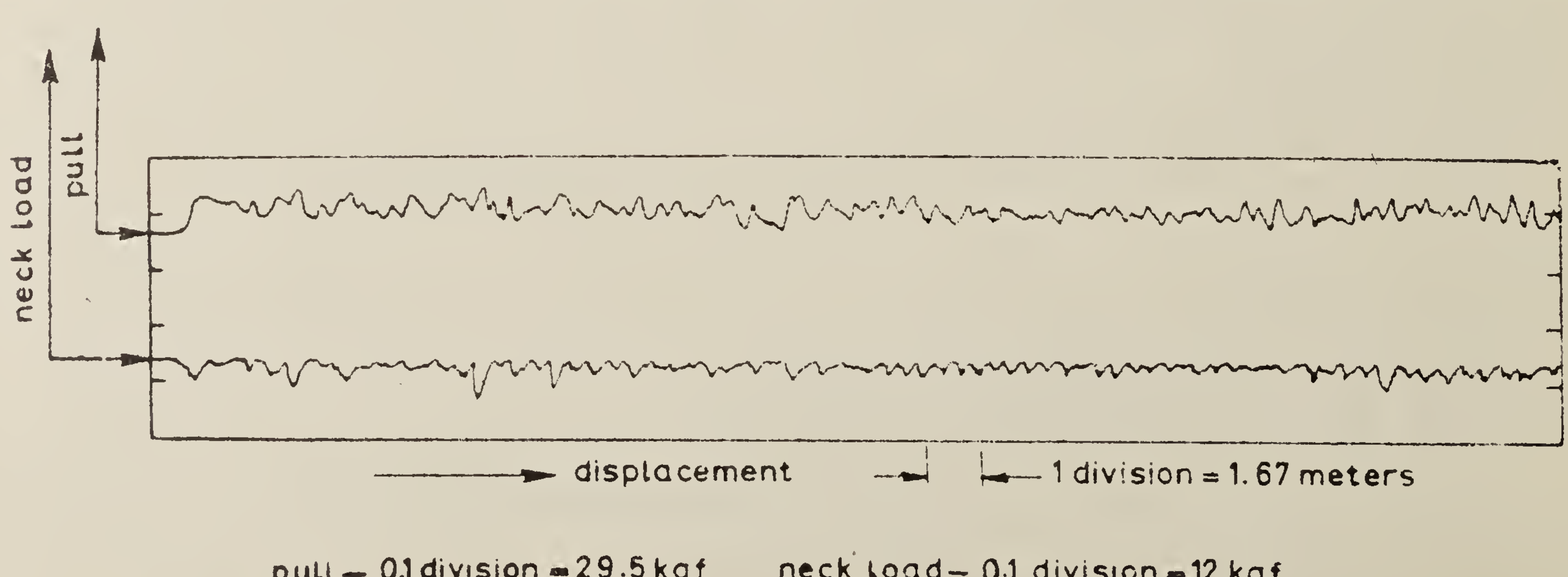

Figure 8. Typical record of pull and neck load.

seen from equation (1c), the low frequency waviness in the bending moment vs time records is due to modulation of the bending moment $W_R y$ due to the neck load by the bending moment Px arising from the discontinuous pull.

To facilitate measurements, all the records were magnified with the aid of an epidiascope. The heights of peaks and valleys in each record were estimated to an accuracy of ± 0.1 mm*.

The relatively high frequency low amplitude peaks in these records were attributed to dynamic effects arising partly from the wheel and terrain interaction and partly from the variation in the motion of the bullocks. To filter off most of these disturbances only peaks/valleys of amplitude greater than about 0·5 mm were measured and used in the analysis.

6.1 *Analysis of pull vs time records*

On each record, the height of the peak(s) h_s at the start of the motion was measured from the zero load (reference) line to estimate the force required to set the cart in motion. This data is used to estimate the static effective coefficient of friction μ_s.

The average pull is determined from

$$\bar{P}_{d\,(\max)} = C_p \sum_{i=1}^{n} h_{pi}/n, \tag{3}$$

where $h_{p1}, h_{p2} \ldots h_{pi} \ldots h_{pn}$ are the amplitudes of the peaks in mm in the pull vs time record, n is the number of peaks (peak(s) h_s are omitted from this analysis), and C_p is the calibration constant in kg/mm. This data is used to estimate the mean dynamic effective coefficient of friction $\bar{\mu}_d$.

From the heights of the valleys h_v in the pull vs time record, the average minimum pull is estimated

$$\bar{P}_{d(\min)} = C_p \sum_{i=1}^{n} h_{vi}/n = \sum_{i=1}^{n} P_{di\,(\min)}/n. \tag{4}$$

The mean amplitude of fluctuation in the pull is calculated from:

$$\bar{P}_{da} = \bar{P}_{d\,(\max)} - \bar{P}_{d\,(\min)}. \tag{5}$$

6.2 *Analysis of bending moment vs time records*

As the bending moment due to the pull acts in a direction opposite to the bending moment due to the upward neck load, a peak in the pull vs time record should correspond to a valley in the bending moment vs time record and vice versa.

From equation (2) the mean neck load $\bar{W}_{Rp}$ can be determined

$$\bar{W}_{Rp} = \sum_{i=1}^{n} W_{Rpi}/n, \quad = \left(C_n \sum_{i=1}^{n} h'_{pi}/n\right) + P_{d\,(\min)} \frac{x}{y}, \tag{6}$$

*For checking the accuracy of measurement with the epidiascope, some records were analysed more accurately with a travelling microscope. This check showed that the error in analysis based on epidiascope measurements was less than 5%.

where h'_{pi} are the heights of peaks in the bending moment vs time record C_n is the calibration constant for conversion of moment data, h'_{pi} in mm of pen deflection to equivalent vertical load or neck load on the bullocks.

The mean neck load $\overline{W}_{Rv}$ is given by

$$\overline{W}_{Rv} = \sum_{i=1}^{n} W_{Rvi}/n = \left(C_n \sum_{i=1}^{n} h'_{vi}/n\right) + \bar{P}_{d(\max)}\frac{x}{y}, \tag{7}$$

where h'_{vi} are the heights of valleys in the bending moment vs time record and n is the number of valleys used in the computation.

Also, $$\overline{W}_{Ra} = \overline{W}_{Rp} - \overline{W}_{Rv}, \tag{8}$$

where $\overline{W}_{Ra}$ is the mean amplitude of the fluctuation in the neck load.

6.3 *Estimation of coefficients of friction*

For eliminating the error due to gradient variations in the terrain in the estimation of $\bar{\mu}_d$, the experimental cart was run in both forward and return directions on the same terrain. If $P_{di(\max)}$ and $P'_{di(\max)}$ are the pull required to negotiate in the forward and return directions respectively on the ith elemental length of the terrain of gradient θ, then from equation (11) of Part 1 (Raghavan & Nagendra 1979)

$$P_{di(\max)}/W_L = \mu_d\,(\cos\theta - (W_{Rvi})/W_L) + \sin\theta, \tag{9a}$$

$$P'_{di(\max)}/W_L = \mu_d\,(\cos\theta - (W'_{Rvi})/W_L) - \sin\theta, \tag{9b}$$

where W_{Rvi} and W'_{Rvi} are the corresponding neck loads in the forward and return directions respectively. (As the cart velocities are quite low, the acceleration a_c is neglected). Hence

$$[P_{di(\max)} + P'_{di(\max)}]/2\, W_L = \mu_d\,\{\cos\theta - [(W_{Rvi} + W'_{Rvi})/2\, W_L]\}. \tag{10a}$$

As for gradients less than 1 in 5, the error due to replacing cos θ by 1 is less than 2% equation (10) is simplified:

$$[P_{di(\max)} + P'_{di(\max)}]/2\, W_L = \mu_{di}\,\{1 - [(W_{Rvi} + W'_{Rvi})/2\, W_L]\}. \tag{10b}$$

If there are n such elemental lengths in the test length, the mean dynamic effective coefficient of friction is given by

$$\bar{\mu}_d = \left\{\sum_{i=1}^{n} 0.5\,[P_{di(\max)} + P'_{di(\max)}]\right\}/n\, W_L\left[1 - \sum_{i=1}^{n}(W_{Rvi} + W'_{Rvi})/2n\, W_L\right], \tag{11a}$$

$$= 0.5\,[\bar{P}_{df(\max)} + \bar{P}_{dr(\max)}]/W_L\,[1 - (\overline{W}_{Rvf} + \overline{W}_{Rvr})/2\, W_L], \tag{11b}$$

where $\bar{P}_{df(\max)}$ and $\bar{P}_{dr(\max)}$ are the mean values of pull, $\bar{P}_{d(\max)}$ (see equation (3)) in the forward and return run respectively, $\overline{W}_{Rvf}$, and $\overline{W}_{Rvr}$ are the corresponding mean

values for the neck load $\overline{W}_{Rv}$ (see equation (7)) for forward and reverse runs respectively. Similarly the mean static effective coefficient of friction is given by

$$\bar{\mu}_s = 0.5\ (\bar{P}_{sf} + \bar{P}_{sr})/W_L\ \{1 - [(\overline{W}_{Rsf} + \overline{W}_{Rsr})/2\ W_L]\}, \qquad (12)$$

where $\bar{P}_{sf}$ and $\bar{P}_{sr}$ are the mean peak load at the start of the motion of the cart in the forward and reverse runs respectively. $\overline{W}_{Rsf}$ and $\overline{W}_{Rsr}$ are the corresponding neck loads in the forward and reverse runs respectively.

7. Discussion of test results

Test records obtained under various operating conditions for carts fitted with pneumatic and steel-rimmed wooden wheels were analysed as described above. The results of these analyses are presented in tables 3 and 4.

The average speed of the cart was in the range of 3 to 4 km/hr. The total weight W_L of the cart fitted with pneumatic and steel-rimmed wooden wheels were 830 kgf (1830 lb) and 932·5 kgf (2056 lb) respectively. The height h of the neck of the bullocks was 100 cm (40 in.).

7.1 *Pull vs time records*

In the case of the cart fitted with pneumatic wheels, the mean static effective coefficient of friction $\bar{\mu}_s$ was about 0·25 on a tar road. On the mud road and the grassy terrain, it was higher and in the range of 0·265 to 0·315. On the tar road, the variation of tyre pressure from 1·4 (20 psig) to 2·1 (30 psig) kgf/cm^2 had no significant effect on $\bar{\mu}_s$. However, on the mud road and on the grassy terrain, this increase in tyre pressure caused a significant increase—from 0·265 to 0·315—in $\bar{\mu}_s$. Also at both the tyre pressures, $\bar{\mu}_s$ was essentially the same for both the mud road and the grassy terrain.

In the case of cart fitted with steel-rimmed wooden wheels, $\bar{\mu}_s$ on the tar road was somewhat lower than on the mud road. It was highest on the grassy terrain.

A comparative study (table 5) indicates that $\bar{\mu}_s$ for the cart with steel-rimmed wooden wheels is significantly higher than $\bar{\mu}_s$ for the cart with pneumatic wheels. It is 16% and 24% higher on the tar road and the grassy terrain respectively. However, on the mud road, $\bar{\mu}_s$ for the former cart is only slightly higher.

The mean dynamic effective coefficient of friction $\bar{\mu}_d$ for the cart fitted with pneumatic wheels was about the same ($\sim$0·08) on the tar road and the mud road. However, on the grassy terrain, it was higher and in the range 0·16 and 0·20. On the tar road and the mud road, tyre pressure variation from 2·1 (30 psig) to 1·4 (20 psig) kgf/cm^2 had no significant effect on $\bar{\mu}_d$. On the grassy terrain the same decrease in tyre pressure resulted in a significant (25%) decrease in $\bar{\mu}_d$.

In the case of the cart fitted with steel-rimmed wooden wheels $\bar{\mu}_d$ on the mud road and the grassy terrain were about 45% and 125% respectively higher than that on the tar road. A comparative study of $\bar{\mu}_d$ for the carts with steel-rimmed wooden wheels and pneumatic wheels indicates that the $\bar{\mu}_d$ for the former cart is 27% and 31% lower on the tar road and the grassy terrain respectively. On the mud road, however, $\bar{\mu}_d$ for the cart with steel-rimmed wooden wheels is only slightly higher.

Table 3. Analysis of data on pull P

Type of wheels	Terrain	Velocity (km/hr)	At the start of motion				Dynamic forces					Mean coefficient of friction	
			$\bar{P}_s$ kgf (lb)	$\bar{P}_s/W_L$	P_{Rs} kgf (lb)	P_{Rs}/W_L	$\bar{P}_{d(max)}$	$\bar{P}_{d(max)}/W_L$	$\bar{P}_{d(min)}$	$\bar{P}_{d(min)}/W_L$	$\bar{P}_{da}/\bar{P}_{d(max)}$	$\bar{\mu}_s$	$\bar{\mu}_d$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Pneumatic wheels; Tyre pressure. 2·1 kgf/cm² (30 psig) W_L=830 kgf (1830 lb)	TR1	F 3·2	228 (503)	0·275	238 (523)	0·286	80·5 (177)	0·097	12·7 (28)	0·015	0·84	0·249	0·083
		R 3·2	151·5 (334)	0·182	167 (367)	0·20	50 (110)	0·060	10 (22)	0·012	0·80		
	MR	F 3·5	224 (494)	0·27	238 (524)	0·286	42 (92·5)	0·050	1·8 (4)	0·002	0·96	0·313	0·07
		R 3·5	243 (536)	0·293	260 (573)	0·313	67·5 (149)	0·081	26·3 (58)	0·032	0·61		
	GT	F 3	243·5 (537)	0·293	259 (571)	0·312	143·5 (316)	0·173	41·5 (91·5)	0·05	0·71	0·314	0·198
		R 3	224 (494)	0·27	239 (526)	0·288	159 (351)	0·192	68·5 (151)	0·082	0·57		
Pneumatic wheels Tyre pressure 1·4 kgf/cm² (20 psig) W_L=830 kgf (1830 lb)	TR1	F 3·1	156 (344)	0·188	167 (367)	0·20	71 (157)	0·086	—9·5 (—21)	—0·011	1·13	0·223	0.091
		R 3·2	184 (406)	0·222	201·5 (443·5)	0·242	70 (154)	0·084	22 (48)	0·026	0·69		
	TR2	F 3·5	205·5 (453)	0·247	218 (479)	0·262	70·5 (155·5)	0·085	18·5 (40·5)	0·022	0·74	0·273	0·08
		R 3·3	210 (463)	0·253	222 (489)	0·267	54 (119)	0·065	10·7 (23·5)	0·013	0·80		
	MR	F 3·5	177·5 (391)	0·214	191·5 (421)	0·23	75·5 (166)	0·091	27 (60)	0·033	0·64	0·265	0·082
		R 3·8	226·5 (500)	0·273	236·5 (520·5)	0·284	52 (115)	0·063	10·5 (23·5)	0·013	0·8		
	GT	F 3	203 (448)	0·245	220·5 (485)	0·265	103 (227)	0·124	24·5 (54)	0·029	0·76	0·267	0·162
		R 3	199·5 (440)	0·24	212 (466·5)	0·255	144 (318)	0·174	64·5 (142)	0·077	0·55		

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Steel-rimmed wooden wheels	TR1	F 3·3	261 (576)	0·28	266·5 (586)	0·285	67·5 (149)	0·072	21 (46)	0·022	0·69	0·266	0·062
W_L=932·5 kgf (2056 lb).		R 3·7	206·5 (455)	0·221	215·5 (474)	0·231	44·5 (98)	0·048	6·3 (14)	0·007	0·86		
	TR2	F 3·85	252·5 (557)	0·271	262 (576)	0·28	48·5 (107)	0·052	9 (20)	0·010	0·81	0·314	0·054
		R 3·85	288·5 (636)	0·309	298 (656)	0·319	49·5 (109)	0·053	16 (35)	0·017	0·68		
	MR	F 3·85	183 (404)	0·196	193·5 (426)	0·207	93 (205)	0·10	56·5 (125)	0·061	0·39	0·301	0·084
		R 3·9	339 (747)	0·363	346·5 (762)	0·371	58 (128)	0·062	32·5 (72)	0·035	0·44		
	GT	F 3·35	339 (747)	0·363	345 (759)	0·369	114·5 (252)	0·122	73·5 (162)	0·079	0·36	0·359	0·132
		R 3·7	287 (633)	0·308	294·5 (648)	0·315	124·5 (274)	0·133	41 (90)	0·044	0·67		

Abbreviations: TR, tar road; MR, mud road; GT, grassy terrain; F, forward; R, return.

Table 4. Analysis of data on neck load W_R.

Type of wheels	Terrain		Velocity km/hr	Stationary cart		At start of motion			Dynamic				
				W_R' kgf (lb)	W_R'/W_L	$\overline{W}_{Rs}$ kgf(lb)	$\overline{W}_{Rs}/W_L$	$\frac{\overline{W}(_{Rs}-W_R')}{W_R'}$	$\overline{W}_{Rp}$ kgf(lb)	W_{Rp}/W_L	$\overline{W}_{Rv}$ kgf(lb)	$\overline{W}_{Rv}/W_L$	$\overline{W}_{Ra}/W_{Rp}$
(1)	(2)		(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Pneumatic wheels	TR1	F	3·2	40·8 (90)	0·049	65·8 (145)	0·079	0·61	49·4 (109)	0·059	34·5 (76)	0·041	0·30
Tyre pressure: 2·1 kgf/cm² (30 psig)		R	3·2	40·8 (90)	0·049	69·4 (153)	0·084	0·7	57 (126)	0·069	53 (117)	0·064	0·07
	MR	F	3·5	40·8 (90)	0·049	79·4 (175)	0·096	0·94	47·3 (104)	0·057	39·5 (87)	0·047	0·165
W_L=830 kgf (1830 lb)		R	3·5	45·3 (100)	0·055	92 (203)	0·111	1·03	59·5 (131)	0·072	56 (124)	0·068	0·055
	GT	F	3	50 (1[illegible])	0·060	88·4 (195)	0·106	0·77	67·4 (148·7)	0·081	67·7 (149·2)	0·081	0
		R	3	50 (110)	0·060	82·5 (182)	0·099	0·65	83·2 (183·4)	0·100	68·1 (150·2)	0·082	0·18
Pneumatic wheels	TR1	F	3·1	45·3 (100)	0·055	57·6 (127)	0·069	0·27	48·7 (107·4)	0·059	48·7 (107·3)	0·058	0
Tyre pressure 1·4 kgf/cm² (20 psi)		R	3·2	40·8 (90)	0·049	81 (178·5)	0·097	0·98	53·1 (117)	0·064	56·7 (125)	0·068	0·07
	TR2	F	3·5	42·2 (93)	0·051	70·7 (156)	0·085	0·68	51·2 (112·7)	0·062	49·8 (109·8)	0·06	0·025
W_L=830 kgf (1830 lb)		R	3·3	51·2 (113)	0·062	71·7 (157)	0·086	0·39	51 (112·4)	0·062	52·3 (115·4)	0·063	0·025
	MR	F	3·5	45·3 (100)	0·055	71 (156·4)	0·085	0·56	54·1 (119·4)	0·065	56·3 (124)	0·068	0·04
		R	3·8	51·2 (113)	0·062	65·5 (144·5)	0·079	0·28	54·6 (120·4)	0·066	49·5 (109)	0·059	0·095
	GT	F	3	55·8 (123)	0·067	84·2 (165·6)	0·101	0·51	65·7 (145)	0·079	67·2 (148·3)	0·081	0·025
		R	3	51·2 (113)	0·062	70·3 (155)	0·085	0·37	69·4 (153)	0·084	63·8 (140·8)	0·077	0·08

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Steel-rimmed wooden wheels	TR1 F	3·3	44 (97)	0·047	48·5 (107)	0·052	0·105	52 (115)	0·056	26·2 (57·8)	0·028	0·50
W_L=932·5 kgf (2056 lb)	R	3·7	42·2 (93)	0·045	60·8 (134)	0·065	0·44	49·6 (109·4)	0·053	31·2 (68·8)	0·033	0·37
	RT2 F	3·85	44 (97)	0·047	66·2 (146)	0·071	0·505	50·7 (111·8)	0·054	22 (48·6)	0·024	0·565
	R	3·85	40·8 (90)	0·044	73·9 (163)	0·079	0·81	49 (108)	0·052	28·7 (63·2)	0·031	0·415
	MR F	3·85	40·8 (90)	0·044	61·2 (135)	0·066	0·50	66·3 (146·2)	0·071	29·4 (64·8)	0·031	0·56
	R	3·9	46·7 (103)	0·05	68·9 (152)	0·074	0·475	54·7 (120·6)	0·059	26·4 (58·2)	0·028	0·52
	GT F	3·35	48·5 (107)	0·052	60·3 (133)	0·065	0·245	71·2 (157)	0·076	36·8 (81)	0·039	0·485
	R	3·7	44 (97)	0·047	62·1 (137)	0·067	0·41	51·4 (113·3)	0·055	20 (44)	0·021	0·61

Abbreviations: TR, tar road; MR, mud road; GT, grassy terrain; F, forward; R, return.

Table 5. $\bar{\mu}_s$ and $\bar{\mu}_d$ for bullock carts with pneumatic wheels and with steel-rimmed wooden wheels.

Terrain	Cart with pneumatic wheels				Cart with steel-rimmed wooden wheels			
	$\bar{\mu}_s$		$\bar{\mu}_d$		$\bar{\mu}_s$		$\bar{\mu}_d$	
	Range	Mean value	Range	Mean value	Range	Mean value	Range	Mean value
Tar road	0·22–0·27	0·25	0·08–0·09	0·085	0·26–0·31	0·29	0·05–0·06	0·058
Mud road	0·265–0·315	0·29	0·07–0·08	0·075	—	0·30	—	0·084
Grassy terrain	0·265–0·315	0·29	0·16–0·20	0·18	—	0·36	—	0·132

For both types of carts, the mean amplitude of fluctuation of the pull $\bar{P}_{da}$ on a tar road is in the range of 68 to 85% of the $\bar{P}_{d(\max)}$. However, on the mud road and the grassy terrain, $\bar{P}_{da}$ for the cart with steel-rimmed wooden wheels is significantly lower.

7.2 *Neck load*

In all these tests, the neck load W'_R on the stationary bullocks (just before they start moving the cart) was set at a value in the range of 40 to 56 kg. At the start of the motion of the cart due to the force exerted by the bullocks the neck load increased considerably. This increase in the neck load i.e., $(\overline{W}_{Rs}—W'_R)/W'_R$ at the start of the motion in the case of the cart with pneumatic smaller wheels was higher; the mean value was 0·62. The corresponding value for the cart with larger diameter steel-rimmed wooden wheels was 0·44.

The increase in the mean neck load $(\overline{W}_{Rp}—W'_r)$ in the moving cart was maximum on the grassy terrain. On the tar road and the mud road, the increase in the mean neck load $(\overline{W}_{Rp}—W'_R)$was about the same for both types of carts. The mean amplitude of fluctuation in the neck load $(\overline{W}_{Ra}/\overline{W}_{Rp})$ was the lowest in the cart with pneumatic wheels inflated to a pressure of 1·4 kgf/cm^2 (20 psig); it was less than 0·1. An increase in tyre stiffness due to increase in pressure from 1·4 to 2·1 kgf/cm^2 resulted in a higher $\overline{W}_{Ra}/\overline{W}_{Rp}$. It was the highest for the cart fitted with stiff steel-rimmed wooden wheels and was in the range 0·37 to 0·61.

It was also observed that the bullocks were subjected to a ground-induced vibratory neck load of low amplitude but of a relatively higher frequency. The ground-induced vibrating load content was significantly higher in the case of the cart fitted with steel-rimmed wooden wheels.

8. Conclusions

A strain-gauge load cell with separate bridges for measurement of the pull and the bending moment in the plane containing the net neck load and pull, was developed and fixed in the longitudinal member of an experimental cart at a section about 30 cm

from the yoke end. The outputs from these bridges were connected to a Kelvin and Hughes pen recorder through separate strain meters and amplifiers. Both the pull and moment measuring systems were finally calibrated *in situ*. A cart fitted first with pneumatic wheels and then with steel-rimmed wooden wheels was tested on three types of terrains—tar road, mud road, and grassy terrain. Pull vs time and moment vs time records were obtained in each test and analysed using the procedure developed.

The analysis of all the test records reveal:

(i) The bullocks pull the cart rather discontinuously at the low veocities (3 to 4 km/hr) at which these carts normally operate. For both types of carts—carts fitted with either pneumatic wheels or steel-rimmed wooden wheels—on the tar road, the mean amplitudes of fluctuation of the pull $\bar{P}_{da}$ is in the range of 68 to 85% of the average pull $\bar{P}_{d\,(\max)}$. However, on the mud road and the grassy terrain $\bar{P}_{da}$ for the cart with steel-rimmed wooden wheels is significantly lower.

(ii) On the tar road and the grassy terrain, the mean static coefficient of friction for the cart with steel-rimmed wooden wheels is significantly higher than for the cart with pneumatic wheels. On the mud road however $\bar{\mu}_s$ for the former cart is only slightly higher.

(iii) The mean dynamic coefficient of friction for the cart with steel-rimmed wooden wheels is 27 and 31% lower on the tar road and grassy terrain respectively. On the dry hard mud road, however, $\bar{\mu}_d$ of the cart with steel-rimmed wooden wheels is only slightly higher than for the cart with pneumatic wheels.

These results show that the dynamic frictional resistance of the terrain ($\bar{\mu}_d$) for the cart fitted with steel-rimmed wooden wheels is lower than for the cart with pneumatic wheels so long the wheels do not dig or sink into the terrain. On a dry hard mud road, $\bar{\mu}_d$ for both types of carts are comparable chiefly due to the increased deformation of the terrain in the case of cart with steel-rimmed wooden wheels. Increase in the width of the wheels would minimise the deformation of the terrain.

(iv) The increase in the neck load on the bullocks was maximum at the start of motion of the cart. Also this increase in the neck load was higher for the cart with pneumatic smaller wheels.

The average increase in the neck load while the cart is in motion was maximum on the grassy terrain. On the tar road and the mud road however this increase in the neck load was about the same for both types of carts.

(v) The mean amplitude of fluctuation in the neck load, $\bar{W}_{Ra}$ was the lowest in the case of cart fitted with pneumatic wheels having a tyre pressure of 1·4 kgf/cm^2. $\bar{W}_{Ra}$ was the highest for the cart fitted with the relatively stiff steel-rimmed wooden wheels.

The ground-induced low-amplitude high-frequency vibratory load content in the neck load was also large in the case of cart fitted with the steel-rimmed wooden wheels. Thus, due to inherent damping, the discomfort caused to the bullocks due to neck load fluctuations is significantly less in the case of cart fitted with pneumatic wheels.

(vi) The experimental results indicate that there is a need to develop an alternative wear-resistant material for the rim of the wooden wheels, which has built-in damping and a stiffness considerably lower than that of steel, e.g., a rubber composite.

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List of symbols

a_c	acceleration of cart in the direction of motion (cm/s^2)
C_n	calibration constant to convert moment data in mm of pen deflection to equivalent neck load (kgf/mm)
C_p	calibration constant to convert pull data in mm of pen deflection to corresponding pull (kgf/mm)
h	amplitude in pull vs time record (mm)
h'	amplitude in moment M_{ll} vs time record (mm)
M_{ll}	bending moment about axis *ll* (figure 1)
M_{nn}	bending moment about axis *nn* (figure 1)
n	number of values or events
P	pull exerted by the bullocks on the cart (kgf)
$P_{di(\max)}$	magnitude of *i*th peak in kgf in the pull vs time record (kgf)
$P_{di(\min)}$	magnitude of *i*th valley in kgf in the pull vs time record (kgf)
$\bar{P}_{d(\max)}$	average maximum pull (kgf)
$\bar{P}_{d(\min)}$	average minimum pull (kgf)
$\bar{P}_{da}$	mean amplitude of fluctuation in pull
P_R	$(P^2+W_R^2)^{1/2}$: resultant force exerted by the bullocks on the yoke
T	torque on the load cell (kgf/cm) (figure 1)
W_L	total load on the cart (kgf)
W_R	neck load on the bullocks (kgf)
$\overline{W}_{Rv}$	average neck load corresponding to peaks in the moment vs time record (kgf)
$\overline{W}_{Rv}$	average neck load corresponding to valleys in the moment vs time record (kgf)
$\overline{W}_{Ra}$	mean amplitude of fluctuation in the neck load
θ	slope of the terrain (degree)
$\bar{\mu}_d$	mean dynamic effective coefficient of friction
$\bar{\mu}_s$	mean static effective coefficient of friction
$\mu\epsilon$	microstrain

Subscripts

- a amplitude
- d dynamic
- f forward journey
- i ith value
- p peak
- r return or reverse journey
- s static
- v valley

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Plate 1

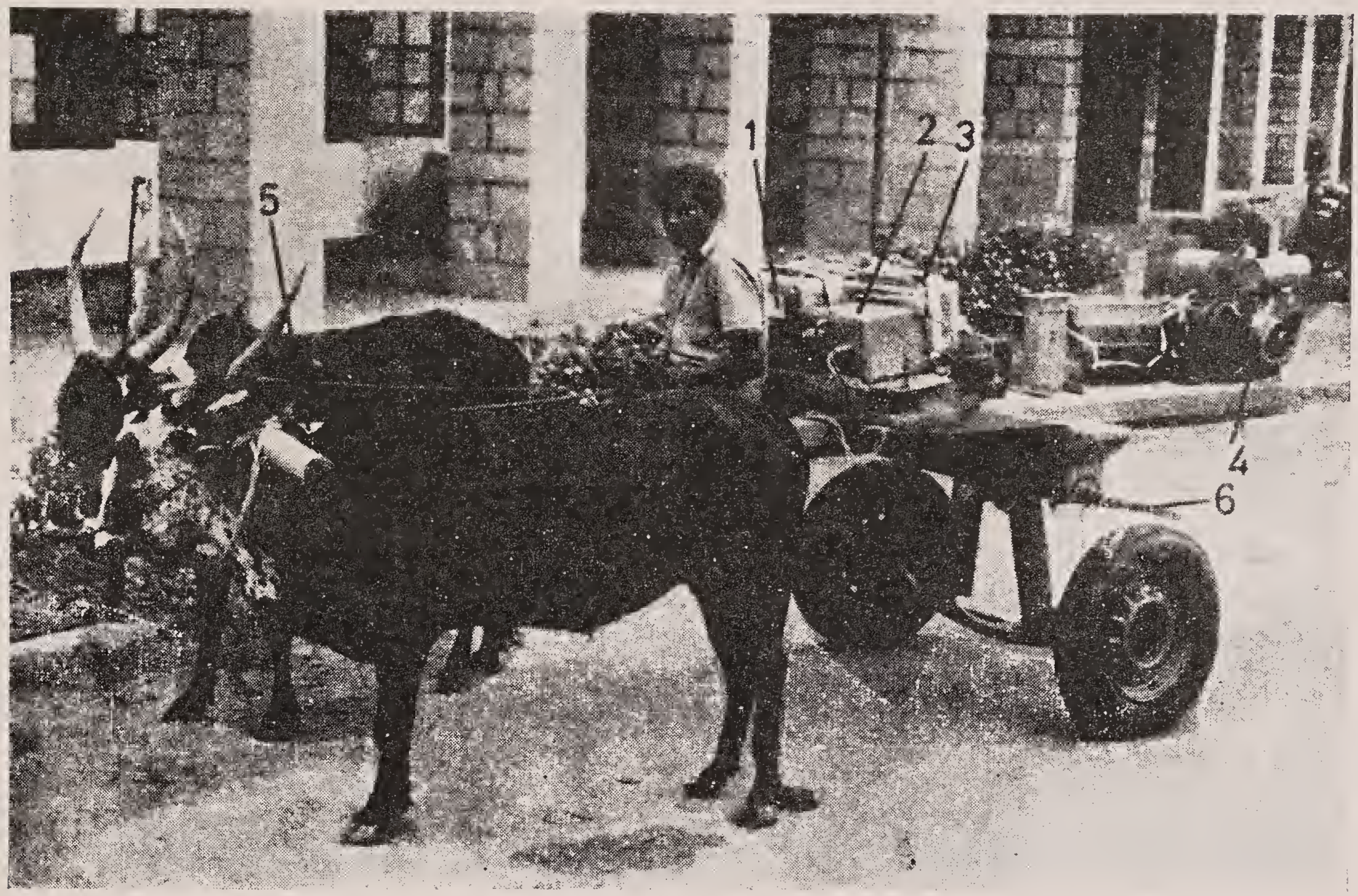

Figure 5. Experimental bullock cart. 1. Strain meter. 2. Kelvin and Hughes recorder. 3. Preamplifier. 4. Engine generator set. 5. Load cell. 6. Axle for steel-rimmed wooden wheels.

A systems approach to rural housing

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Abstract. An attempt is made in this paper to arrive at a methodology for generating building technologies appropriate to rural housing. An evaluation of traditional/ ' modern ' technologies currently in use reveals the need for alternatives. The lacunae in the presently available technologies also lead to a definition of rural housing needs. It is emphasised that contending technologies must establish a ' goodness of fit ' between the house form and the pattern of needs. A systems viewpoint which looks at the *dynamic process* of building construction and the *static structure* of the building is then suggested as a means to match the technologies to the needs. The process viewpoint emphasises the role of building materials production and transportation in achieving desired building performances. A couple of examples of technological alternatives like the compacted soil block and the polythene-stabilised soil roof covering are then discussed. The static structural system viewpoint is then studied to arrive at methodologies of cost reduction. An illustrative analysis is carried out using the dynamic programming technique, to arrive at combinations of alternatives for the building components which lead to cost reduction. Some of the technological options are then evaluated against the need patterns. Finally, a guideline for developments in building technology is suggested.

Keywords. Rural housing; alternative technologies; building technologies; systems analysis; building materials; compacted soil block; polythene-stabilised soil roof; dynamic programming; cost reduction; energy conservation; performance; self-reliance; development; structural analysis; transportation; traditional technologies; modern technologies; construction; durabilty; needs.

1. Introduction

The housing shortage in India is believed to be anywhere between 12 to 30 million units, and the shortfall is increasing. The inequalities in access to land and finance are considered to be the major hurdles in the way of massive housing programmes. It would, however, be misleading to believe that land distribution and housing loans by themselves will solve the basic problem. A massive programme of investment on housing will only accentuate inequalities if the building technologies are inappropriate. Hence, there is a need to look into the technological issues arising from housing needs. Since the bulk of the housing shortage is to be found in rural areas, this discussion is centred mainly around the problem of rural housing.

In the past, the housing needs of societies were successfully met by traditional technologies evolved and perfected over centuries. These technologies and the associated indigenous forms were conditioned and moulded by the skills and resource endowments of each region. Some of these traditional houses represent the finest examples of house forms, achieving complete harmony between life-styles and the built environment. This equilibrium, however, has been upset with modernisation. Although traditional construction techniques have been perfected over long

periods, they lack the flexibility to keep pace with the changing patterns of resource availability (material and human resources) and individual aspirations—thus, many of the traditional methods of building have become inadequate. At the same time, ' modern ' building technologies too are becoming unsatisfactory, either because they entail intensive energy usage or lead to a total dependence on urban products or are too expensive. The need for alternative building technologies is hence fairly clear.

2. Rural housing needs

The concept of ' low-cost housing ' has led to the misleading notion that cost reduction alone should be the chief concern of alternative building technologies. While the importance of cost reduction in house construction should never be minimised, its over-emphasis has led to a proliferation of low-cost structures which are often totally inadequate as ' houses '. It is useful to recall, in this context, the statement made by Alexander (1964): ' Design is not an optimisation problem '. Cost optimisation *per se* is a narrow one-dimensional view of what is, in fact, a multi-dimensional housing problem. It appears unlikely that all the dimensions of the problem can be adequately represented by a single objective function, such as building cost.

The test of a ' solution ' to the housing problem lies in its ability to meet a variety of shelter needs generated by the rural context. The large set of disparate shelter needs defines a multi-dimensional pattern, and the success of a housing ' solution ' is to be measured by the ' goodness of fit ' between the design profile and the pattern of needs. A clear enunciation of these needs is, therefore, a pre-requisite for the development of appropriate building technologies.

The housing needs of rural communities can be broadly classified into two categories:

(i) the felt needs of the house owner, and
(ii) the development needs of the community.

These two categories reflect the fact that the individual is part of society, and for the survival of the social system, the needs of the individual and those of society must be simultaneously met. The processes of centralised socio-economic growth have often thrown up technological options which satisfy the felt needs of the individual while eroding the self-reliance of the community as a whole. The extensive dependence on an urban product like the Mangalore tile is a case in point. This does not mean that there has to be a total ban on the use of urban products for rural housing. One can conceive of a symbiotic relationship between city-based and rural technologies.

A representative, but by no means exhaustive, list of housing needs is presented below:

(a) *Felt needs of the house owner:* (i) durable building elements (ii) leak-proof roofs (iii) thermal comfort and ventilation (iv) security (v) shelter for livestock (vi) storage space for grain, fodder and firewood (vii) design which enables growth (viii) cost reduction (ix) aspirations towards better housing.

(b) *Development needs of the community:* (i) self-reliance in building technologies (ii) conservation of energy (iii) local participation and employment generation (iv) environmental harmony (v) maximum use of local resources and skills.

It is interesting to note that traditional technologies, like mud walls, and roofs using thatch and country tiles, satisfy most of the development needs, but do not meet several felt needs of the house owner. Again, certain technologies, like Mangalore tiles, burnt bricks and mill-sawn timber, fulfil most of the individual felt needs, but are incompatible with many development goals. Thus, there is an overwhelming case for a set of appropriate alternatives which can eliminate the conflicts between individual and community needs.

3. Systems approach to match technologies and needs

An understanding of the felt needs of the house owner and the development needs of the community leads to a definition of the *performance* required of eligible technologies. Further, these performance requirements, when articulated with sufficient clarity, often suggest the right technologies. In this attempt to match technologies to the need patterns, an integrated systems view of the building is often helpful.

There can be two kinds of system viewpoints on rural buildings. Firstly, one may emphasise the *dynamic process* of production of materials, transportation, construction, and renewal, where the temporal chain of building-related events (activities) are examined. Secondly, one can take a *static structural* system view where the emphasis is on the interacting building components which are in equilibrium under a set of environmental forces.

Although the two views appear to be antithetical, they may be regarded as mutually complementary, and a total view of rural buildings must synthesise both the standpoints. For instance, some felt needs like durability of building elements and thermal comfort, and some development needs like use of local materials and conservation of fuel energy, must be taken into account at the level of building materials production. The dynamic process view is relevant in such situations. On the other hand, the static structural system view is important while considering issues like cost reduction and growth-oriented design.

4. Building construction—the process view

The construction of buildings in rural areas generally involves three distinct operations:

(i) production/procurement of materials,
(ii) transportation to site, and
(iii) construction.

The above operations may now be examined vis-a-vis rural housing needs in order to arrive at suitable building technologies.

Consider the development need of conserving energy. It has been shown elsewhere (Jagadish 1979) that the energy devoted to the transportation of bulk materials (like soil, bricks, stones) is dependent on the transportation mode (head-load/wheelbarrow/bullock-cart/tractor/truck) and for each mode, on the distance from which the material is being transported. In particular, each transportation mode is the cheapest within a particular distance regime. But, the energies and costs associated

with transport from a longer distance are always greater than those for a shorter distance even though the cheapest modes are used for each of these distances. There is an unambiguous implication from this analysis: to prevent the energies and costs associated with transportation from dominating the total building costs, it is essential (i) to rely on materials which can be procured from the shortest possible distance, i.e., on ' local ' materials, and (ii) to transport these materials by the most inexpensive mode.

Granted that the transport component of the energy and costs is restricted to a reasonable percentage (say 10%), the *production* of building materials is the most important item in the total energy and costs of the building. Hence, the efficiency (in terms of energy and costs) of the production of building materials becomes a crucial problem. For example, the fact that the average energy content of a burnt brick is about 1500 kcals/brick, and that this energy is obtained from firewood (about 0·32 kg/brick) means that a massive house-building programme cannot be sustained with bricks burnt with firewood as fuel.

The durability of building elements is another important need (in this case, a felt need of the house-owner) which must be considered in the production of basic building materials. The durability of a building is directly determined by the quality and performance of the materials that are used in its construction. Figure 1 shows schematically the possible modes of producing local and durable building materials. Soil-stabilisation provides a low-energy alternative to the usual burning technique in producing durable building blocks and roof coverings. Local production of lime-based cements can lead to many alternative ways of stabilising soil. Again, the well-known copper-chrome-boric acid treatment can provide durable bamboos for roof structure in place of timber. The use of agro-fibres as reinforcements, either in stabilised soil or in plastics, opens up other possibilities of producing durable roof coverings.

Another important development need, viz., self-reliance in building technologies, must be considered in the operations of materials production, transportation and construction. Self-reliance is particularly important in the matter of construction.

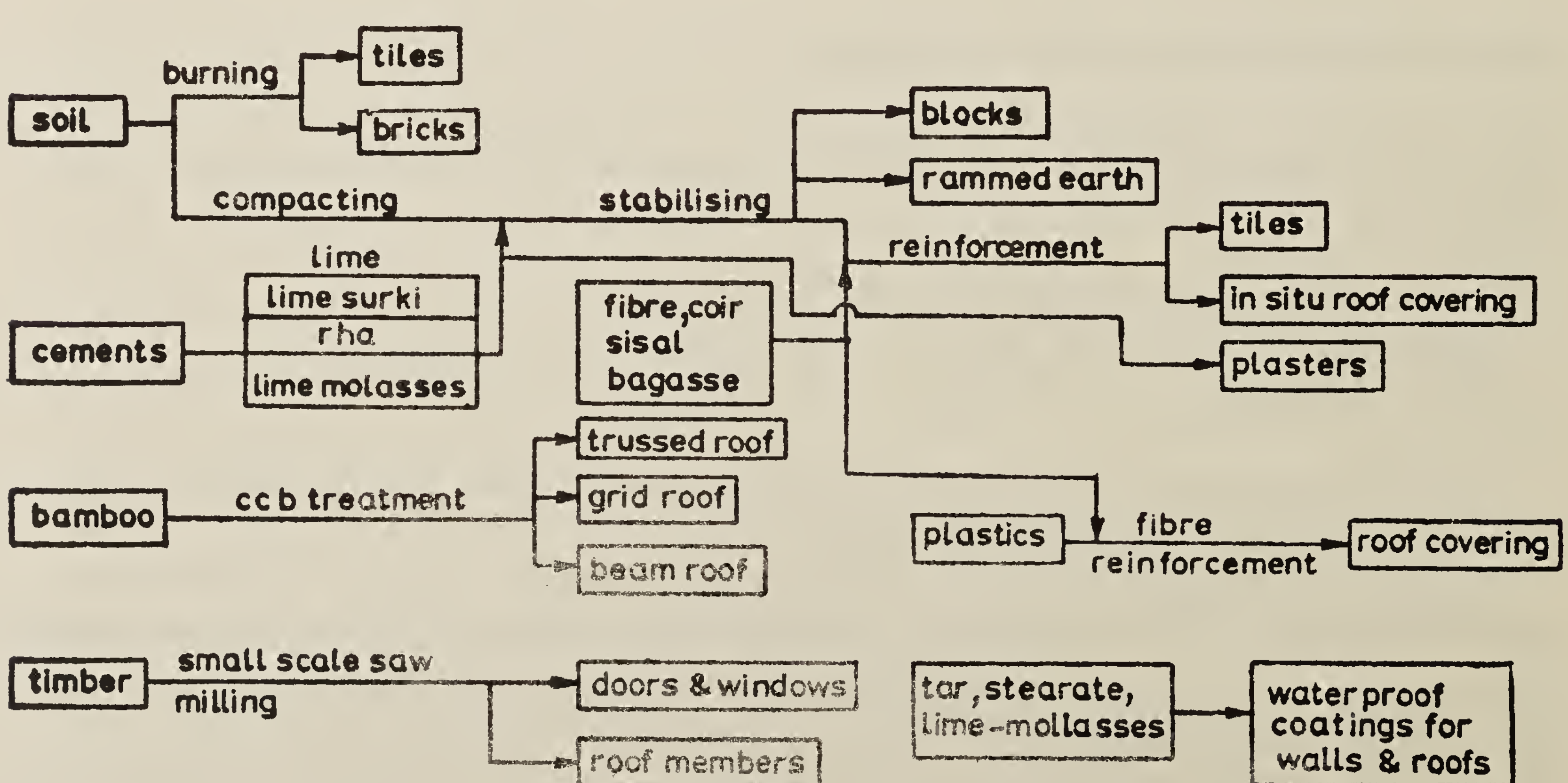

Figure 1. Alternative building materials and technologies.

Thus, the process view provides a systematic approach to designing alternative building technologies which fulfil several housing needs, such as, energy conservation, self-reliance, cost reduction and increased durability of building elements.

5. Examples of alternative building technologies

5.1 *The compacted soil block*

The choice of soil as a material for wall construction is perhaps obvious due to its abundance and very low cost. Its performance under exposure to rain, however, leaves much to be desired. The conventional way of imparting durability and strength to mud is through a burning operation which incidentally entails significant thermal energy consumption. Compaction and stabilisation of soils to produce durable walls present a low-energy alternative to burning.

The compaction may be carried out *in situ* as in rammed earth walls or one may produce compacted soil blocks using manually operated machines like the Ellson Block Master or the Cinva Ram. Such blocks generally have good dry strength (between 20 to 50 kg/cm^2) and lead to relatively thinner and well-shaped walls. The durability of walls using compacted soil blocks is generally dependent on the clay content in the soil. Though a soil with sufficient clay content (10 to 20%) may produce good blocks, it is desirable to make compacted and stabilised blocks for use in strategic locations of a building like load-bearing pillars, arch construction, etc. The commonly-used stabilisers are: (a) lime ($\sim$ 3% by weight), (b) cement (3 to 5% by weight) and (c) lime surki ($\sim$ 10% by weight). Lime stabilisation is effective only if the soil has adequate clay content. Cement and lime surki can be used to stabilise the soil provided the soil is not too clayey. Use of lime and lime surki for soil block stabilisation has been tried extensively at the Ungra Extension Centre of the Indian Institute of Science, in connection with the ASTRA programme for generating appropriate technologies.

This technology represents an attempt to improve the performance of a local material like soil, while satisfying the goals of development discussed earlier. It holds the promise of providing a technique of block production which is accessible to the poorest in villages.

5.2 *The bamboo-polythene-stabilised soil roof*

Bamboo probably represents an obvious choice for the roof structure, by virtue of its excellent strength and low cost. Often, the price per running metre of bamboo is about one fourth of the structurally equivalent timber scantling. Its durability, which is open to question, can be vastly improved by the copper-chrome-boric treatment.

In this roofing technology, the structure is provided by 10 cm diameter bamboos spaced at 30 to 45 cm and the space in-between is covered by closely-spaced split bamboos. All the bamboos are treated by dipping in copper-chrome-boric solution. The roof covering consists of palm mat and polythene sheet with a stabilised soil cover of 4 to 5 cm. The stabilised soil is covered by a thin layer of treated thatch. Figure 2 shows a sectional view of such a roof. The different elements in the roof

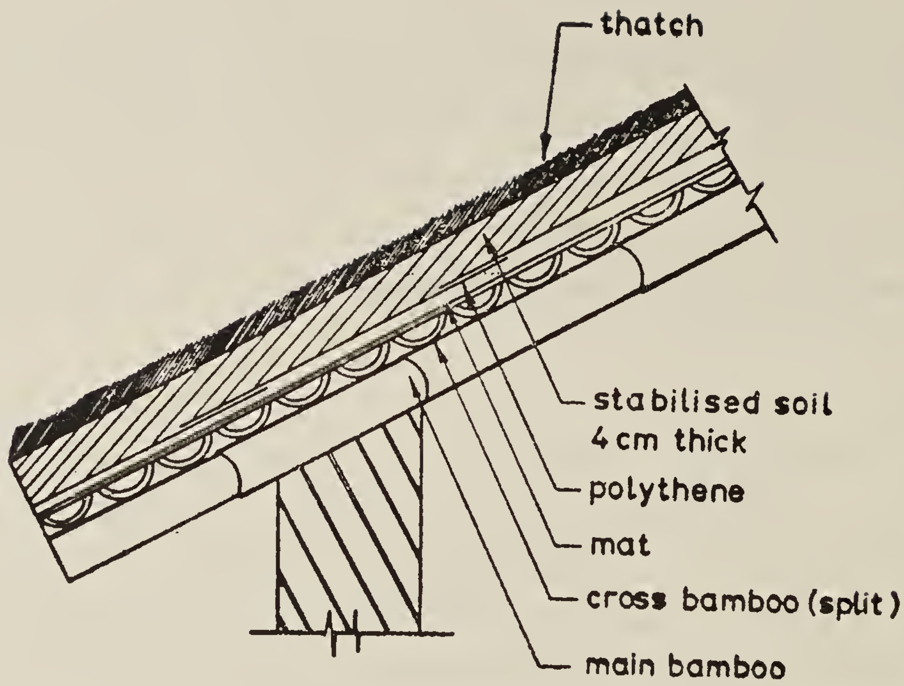

Figure 2. Sectional view of polythene + stabilised soil roof.

have been chosen to meet the various functional requirements. The polythene sheet provides the water-proofing, while the soil cover protects the polythene against sunlight and cuts down the flow of solar heat across the roof. The thatch covering prevents erosion of stabilised soil due to rain impact and water flow besides reducing absorption of solar heat. The combination of different materials is necessary since there is no single local material which can fulfil the many functions required of a roof. The polythene sheet and the treatment chemicals represent the only concession to urban products.

In this mode of roofing, the use of local materials like bamboo and soil along with local skills has been emphasised. While a stabiliser like lime surki is not available today, it can be easily produced in small-scale plants. It goes without saying that the local production of a cementitious material like lime surki is crucial to the development of alternative building technologies.

As part of such a new thrust in building research, there has to be a specific emphasis on the development of building materials. From the standpoint of the felt needs and development needs listed earlier, some of the alternative materials which need to be explored are the following:

(i) compacted, stabilised soil for wall construction,
(ii) treated bamboo for the roof structure,
(iii) stabilised soil, and improved, locally burnt tiles, for roof covering,
(iv) local cements for soil stabilisation and plastering purposes,
(v) water-proofing agents for improving the performance of soils, and
(vi) plastics and new materials based on plastics.

In this new thrust, one must not aim for *the appropriate technology.* Such an approach could lead to a static and rigid solution which may easily be left behind by a changing society. The needs of the community and the aims of development are in a state of continuous flux. The mechanism of technology generation must be dynamic enough to respond to these changes. In this view, the right technology does not emerge merely by an intense programme of research and development. It is obvious that the community which uses a technology must have a decisive say

in its choice. Technology generation and its choice must be a highly interactive process, each providing the momentum and direction for the other. In such an approach, the evolution of technology almost mimics biological evolution. The richness of technological variety at society's disposal is then a pre-condition for the emergence, by a process of natural selection, of satisfactory technologies—and this pre-condition is particularly important for building technologies.

6. The building as a structural system

A single-storeyed building may be considered to consist of four essential structural components, viz., (i) roof covering, (ii) roof structure, (iii) walls and (iv) foundation. These components serve to create a built environment while transferring the external loads to the earth.

According to the structural systems viewpoint, cost reduction can be effected by optimising the structural efficiency of the total system through a consideration of feasible alternatives for each component. The cost-optimal solution can be obtained by scanning the whole range of combinations of alternatives using the dynamic programming technique.

Though a rigorous analysis should consider all possible alternatives, the following limited set of alternatives (for the four structural components) shall be considered in order to carry out an illustrative exercise.

Building component	*Alternatives*
1. Roof covering	(a) Thatch
	(b) Mangalore tiles
	(c) Polythene-stabilised soil
	(d) Soil
2. Roof structure	(a) Double lean-to in bamboo
	(b) Collar-beam truss in bamboo
	(c) Timber and bamboo flat roof
3. Walls	(a) Burnt brick
	(b) Compacted soil block
	(c) Stone
	(d) Masonry pillars + non-load bearing walls
	(e) Stone pillars + non-load bearing walls
	(f) Timber pillars + non-load bearing walls
4. Foundation	(a) Continuous stone and mud foundation
	(b) Discrete stone and mud footings

Component alternatives like 1(c) and 3(b) represent innovative techniques which may be examined along with the other traditional solutions. The options chosen for the different components are not completely independent. For instance, foundation design 4(a) is relevant only for continuous wall options in 3(a), 3(b) and 3(c).

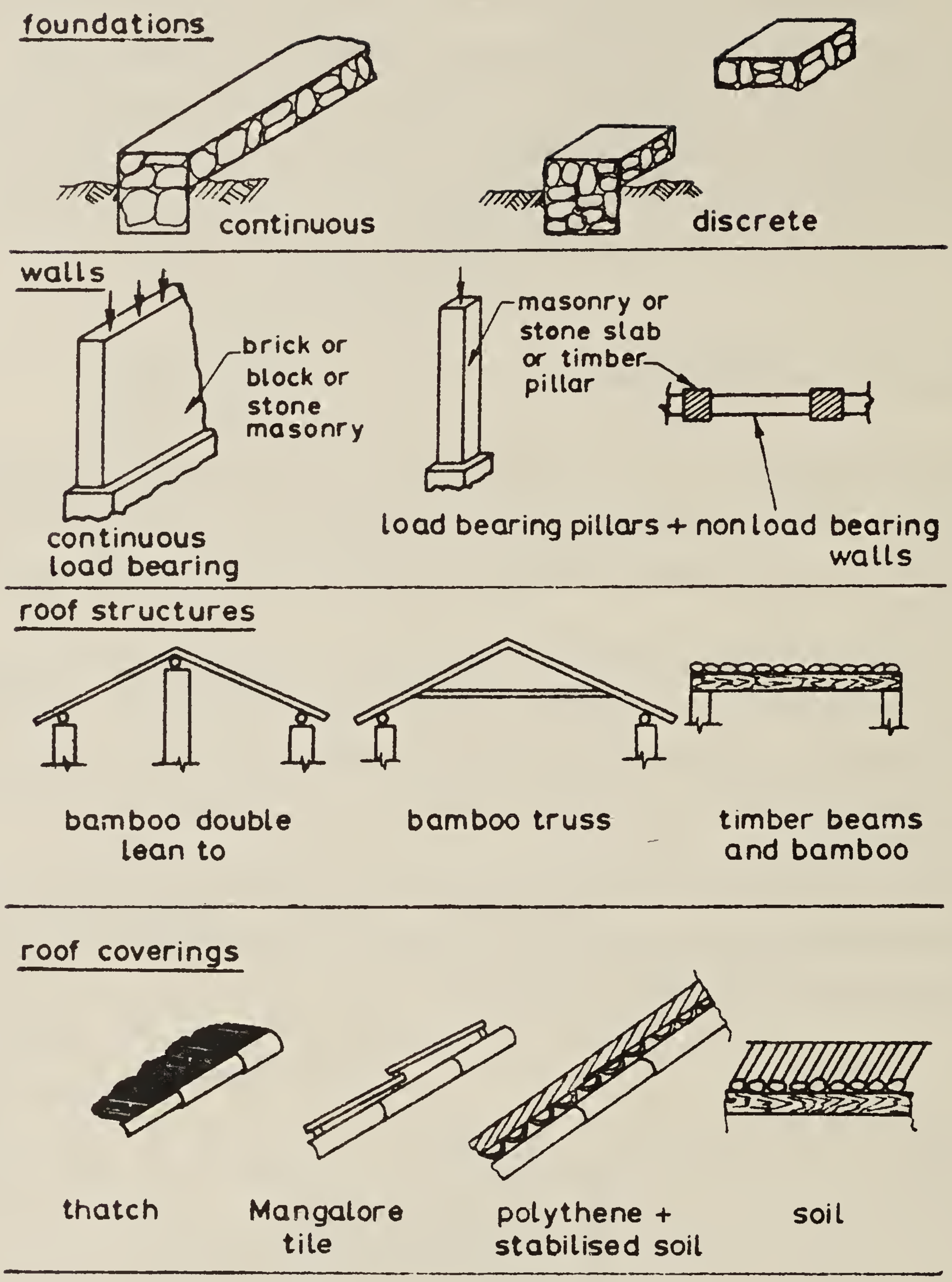

Figure 3. Building component alternatives

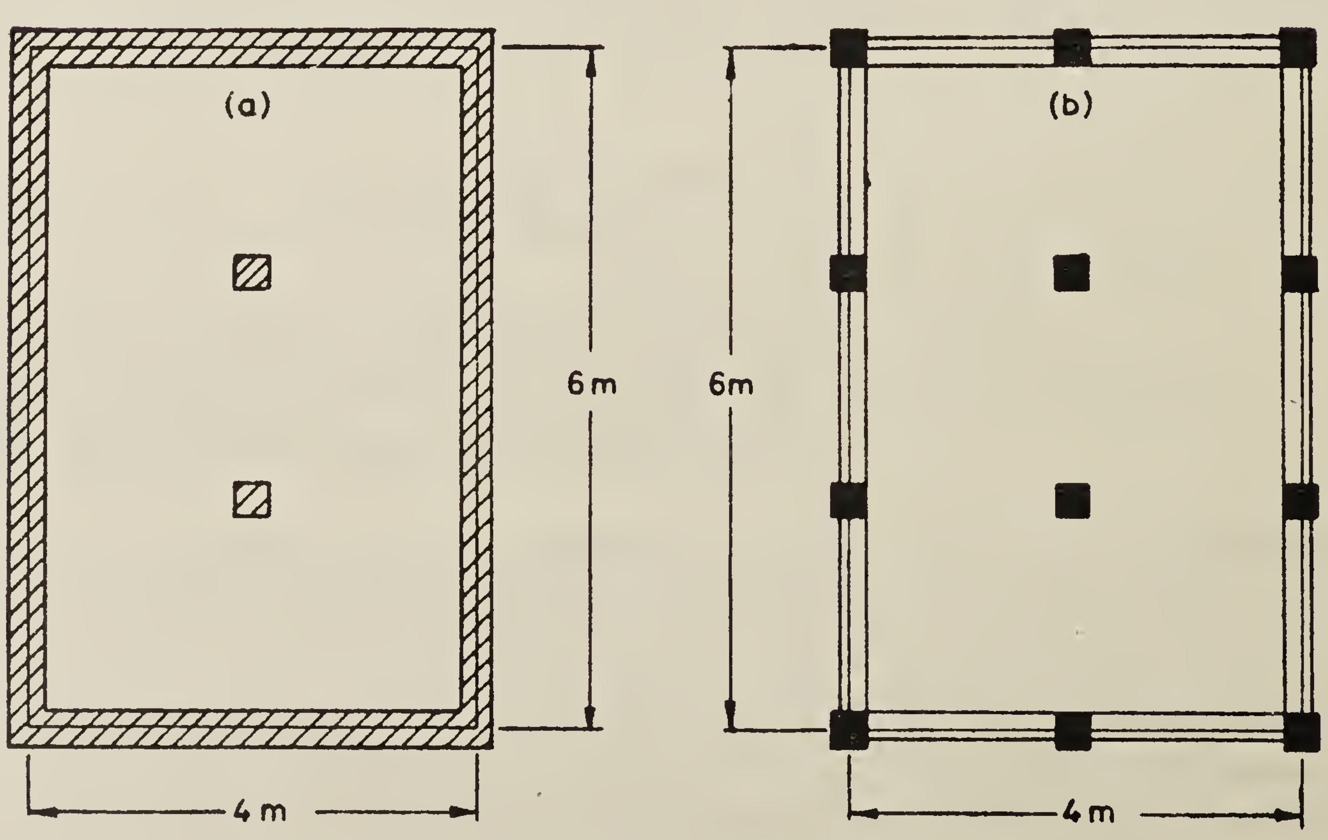

Figure 4. Alternative scheme for wall constructions.

Table 1. Building structure design for cost reduction

Roof covering and design roof load	Optimal components		Foundation	Total cost of structure (Rs)
	Roof structure	Walls		
Thatch (45 kg/m²)	2(a): 8 cm bamboos at 60 cm	3(d): pillars at 3 m spacing	4(b): footings at 3 m	1080
Mangalore tiles (00 kg/m²)	2(a): 10 cm bamboos at 60 cm	3(d): pillars at 3 m spacing	4(b): footings at 3 m	1430
Polythene+stabilised soil (130 kg/m²)	2(a): 10 cm bamboos at 45 cm	3(d): pillars at 2 m spacing	4(b): footings at 2 m	1500
Soil (440 kg/m²)	2(c):	3(b): continuous soil block wall, 30 cm thick	4(a):	2340

Again the timber and bamboo flat roof structure in 2(c) corresponds only to the roof covering 1(d). With this coupling in the component options, a total of 39 building designs must be examined for cost optimisation. The various component designs are also illustrated in figure 3.

The analysis under discussion looks only at the cost of the building structure, rather than that of the entire building, i.e., the cost of doors, windows, flooring and finishes is not considered. It appears reasonable to concentrate on the building structure in the first attempt at cost reduction, because, especially in rural areas, it represents more than 75% of the cost of the entire building.

For purposes of numerical study, a typical rectangular building with a central line dimension of 4 m × 6 m will now be considered. The plan view with two categories of wall design is shown in figure 4. While considering alternatives involving the traditional soil roof, however, a 3 m × 8 m building has been considered since spans more than 3 m are unrealistic for soil roofs. This variation will not make a significant difference in the overall cost analysis, since the volume of walls and foundations is increased only by 10% for this roof. The detailed steps in optimisation are presented in tabular form in the appendix. As a result of the analysis, for each choice of roof covering, the best combination of structural options leading to the lowest cost solution is obtained. The result is summarised in table 1.

This means that out of 39 possible designs, only four optional design combinations need be chosen.

It is now desirable to evaluate these four building designs vis-a-vis the rural housing needs listed earlier. In other words, a cost-performance relationship would help in the assessment of the four cost-optimised buildings. This opens up the question of rating these buildings against each performance requirement and arriving at an overall ranking based on the distribution of ratings. The procedure bristles with

Table 2. The technology-performance matrix

		Thatched roof	Mangalore tile	Polythene+ stabilised soil	soil roof
	Durability	C	B	B	B
	Water leakage	C	B	B	C
Felt needs	Thermal comfort	A	C	B	B
	Cost reduction	A	B	B	C
	Social aspiration	D	A	C	C
	Self reliance	A	C	B	B
	Local participation	A	B	A	B
Development needs	Full energy conservation	A	B	B	B
	Environmental harmony	—	—	—	—
	Local resources & skills	A	C	B	B
	Rank	4	2	1	3
	Cost (Rs)	1080·0	1430·0	1500·0	2340·0

difficulties, and the issues involved therein are discussed at some length by Reddy (1979). In the ideal situation, one would use a detailed survey regarding villagers' opinion of the building designs with reference to the felt needs.

In the absence of such a detailed study, an *ad hoc* procedure of ranking the designs has been adopted in this paper. Table 2 presents a matrix of grades against each need for the four technological options. The grades may be interpreted as follows: A means ' very good ', B means ' satisfactory ', C means ' uncertain or barely satisfactory ' and D means ' unsatisfactory '. If one aims at a goodness of fit between the technology and the pattern of needs, the performance grades must be more or less uniform varying only between As and Bs. The presence of Cs and Ds emphasises the points of mismatch.

One can now arrive at an approximate ranking of these four designs. The polythene + stabilised soil roof seems to score over others because of a large number of Bs and only one C. The Mangalore-tiled building takes the second place, and the soil-roofed one the third place. The thatched roof takes the fourth place because of a D and two Cs, in spite of its excellent fulfilment of development needs. Thus, there are a range of solutions with different performances and costs.

In this ranking, the soil roof is an interesting case, because it is the most expensive solution (of the four considered here) even though it only ranks third in performance. Since its performance is not commensurate with its cost, the soil roof solution must be rejected.

If the soil roof is ignored, the other solutions represent *improvement in performance achieved with increases in cost.* Although the number of solutions in this illustrative analysis is inadequate, the approach used here merits serious consideration because technological developments can generate more solutions with costs in the range spanning thatched and soil roofs. And, if these solutions display a positive correlation between performance and cost, several important conclusions follow.

(i) The search for ' *the* low-cost house ' becomes meaningless.

(ii) What must be generated is a *hierarchy of housing solutions,* each one being costlier, but achieving a better performance, than the ones lower in the hierarchy.

(iii) Such a hierarchy enables a prospective house-owner to choose the particular solution according to his means.
(iv) The hierarchy must also satisfy an important requirement: it must permit dynamism and flexibility, so that even the cheapest house can, by incremental increases of expenditure, move up in the hierarchy, i.e., up the performance scale.
(v) The particular set of solutions constituting the hierarchy must not be a static set; it must be a dynamic set with technological development continuously generating new solutions which achieve greater and greater improvements in performance with smaller and smaller cost increments.

It must again be emphasised that, for satisfactory solutions to emerge, there must be a large number of alternatives to choose from. The methodology used in this paper may be used to screen a sufficient number of contending building component alternatives such that a fairly large number of optimal building design options can be selected.

7. Some directions for developments in building technology

The above illustrative analysis can be extended to define some directions along which technological development may proceed.

The four solutions, which were considered for illustrative purposes, correspond to different values of design roof load.

The cost break-up of the various components for the four optimal structures can, therefore, be presented in figure 5, as a function of the design roof load; the four roof

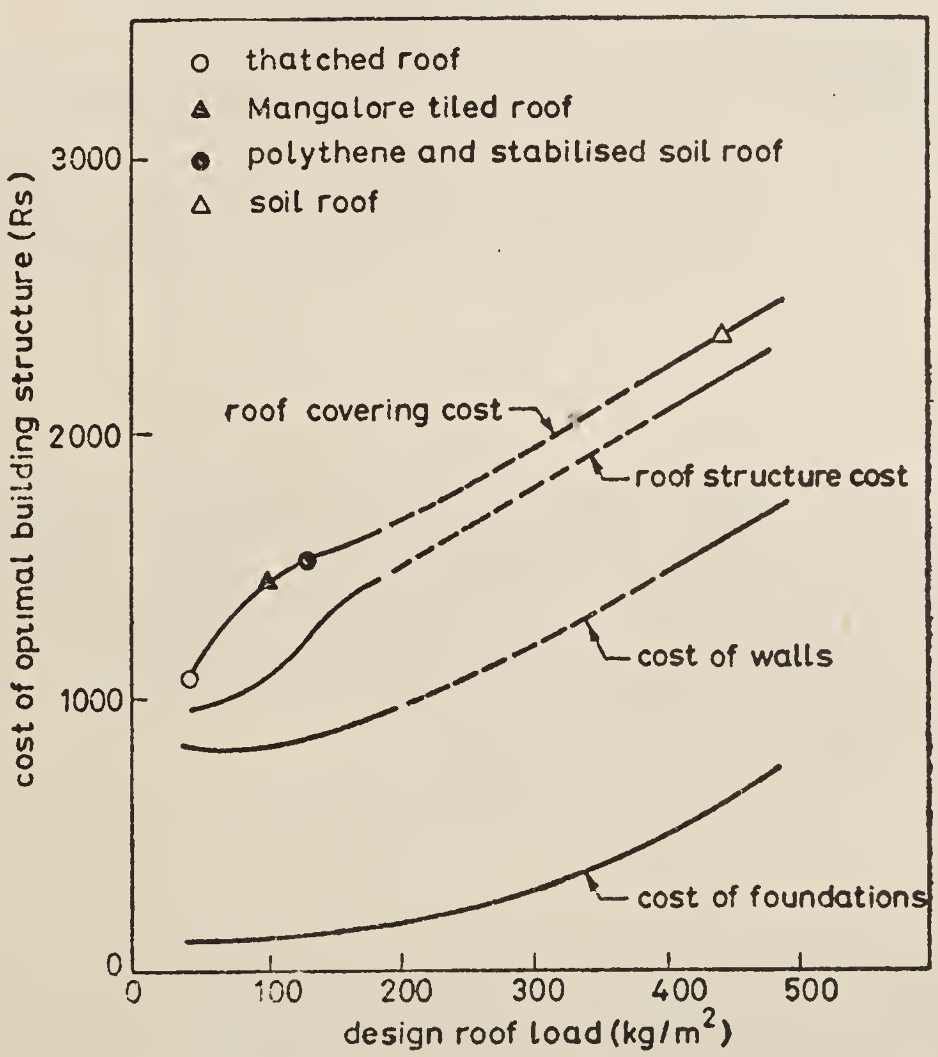

Figure 5. Building cost versus Design roof load

coverings selected provide four points on the curve, where three points are clustered to the left, and the fourth, corresponding to the rather heavy soil roof, is to the right extremity of the curve. While the information in between is lacking at present due to the absence of roof coverings with intermediate weights, one can evaluate the broad trend of costs of roof structure, walls and foundations for the hypothetical roof coverings.

The following conclusions emerge from this figure.

(i) In the optimal structure, the cost of walls varies between 40% to 70% of the total cost. The higher figure of 70% is obtained for thatch-roofed houses.
(ii) Foundation costs are relatively low (less than 10% of the total cost) when discrete footings are used. This means that the design using load-bearing pillars and footings is responsible for the reduction of foundation cost. When roof loads are in excess of 400 kg/m^2, discrete footings are no longer feasible and foundation costs rise steeply to 25% of the total structure cost.
(iii) As roof loads are varied between 45 kg/m^2 to 100 kg/m^2, the costs of roof structure, walls and foundations remain practically constant. The essential difference between thatched and Mangalore-tiled buildings lies in the cost of the tiles. The total cost jumps by about 33% as a change is made from thatch to tiles.
(iv) To keep costs low, the roof covering must be such that the design roof load is not more than 100 kg/m^2 and its cost must be less than Rs 10 per square metre.

The above conclusions clearly indicate that any new thrust in reduction of building cost must come through

(a) alternative wall-construction technologies,
(b) designs using load-bearing pillars and footings, and
(c) new developments in light-weight, cheap roof-coverings.

They also suggest the need to consider a site + service + *load-bearing structure* scheme in place of the site + service schemes now being adopted in housing programmes.

The author is deeply indebted to Professor A K N Reddy for his patient encouragement and invaluable suggestions. Thanks are also due to the Environmental Research Committee, Department of Science and Technology, for supporting the building activity at the Ungra Extension Centre of the Institute, through which the experience underlying this paper was derived.

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Appendix 1. Cost optimisation of building structure. Stage 4. Foundation: stone-in-mud construction. Rate: Rs 60 per cubic m; Assumed bearing capacity of soil: 1 kg/cm²

	Option	Plan dimensions (m)	Volume of foundation (cubic m)	Cost (Rs)	Permitted foundation load (kg/m)
4(a)	Continuous	4×6	9·54	572·4	4920
	0·6×0·75 m	3×8	9·9	594·0	4920
4(b)	1 footing 0·6×0·6 ×0·75 m 2 m spacing	4×6	3·24	194·4	1478
(4b)	2 footing 0·6×0·6 ×0·75 m 3 m spacing	4×6	2·70	162·0	986
(4b)	3 footing 0·45×0·45 ×0·75 m 2 m spacing	4×6	1·82	109·2	832·5
(4b)	4 footing 0·45×0·45 ×0·75 m 3 m spacing	4×6	1·52	91·2	555

Appendix 2. Stages 3 and 4. Walls+foundation, Analysis carried out for several cases of applied wall loads. (a) Load on wall = 60 kg/m (thatched roof)

	Wall design	No. of pillars	Cost (Rs)	Volume of non-load bearing walls (cubic m)	Cost (Rs)	Load on foundation (kg/m)	Foundation (Rs)	Cost of wall + foundation (Rs)
3(d)	Masonry columns at 3 m spacing	10	170·0	11·88	570·0	170·6	4(b)-4: 91.0	831·0
3(e)	Stone pillars at 3 m spacing	10	198·0	13·5	648·0	144	4(b)-4: 91·0	937·0
3(f)	Timber pillars at 3 m spacing	10	300·0	13·5	648·0	70	4(b)-4 91·0	1039·0

(b) Load on wall = 120 kg/m (Mangalore-tiled roof)

	Wall design	No. of pillars	Cost (Rs)	Volume of non-load bearing walls (cubic m)	Cost (Rs)	Load on foundation (kg/m)	Foundation option and cost (Rs)	Cost of wall + foundation (Rs)
3(d)	Masonry pillars at 3 m spacing	10	170·0	11·88	570·0	264	4(b)-4: 91·0	831·0
3(e)	Stone pillars at 3 m spacing	10	198·0	13·5	648·0	203	4(b)-4: 91·0	937·0
3(f)	Timber pillars at 3 m spacing	10	300·0	13·5	648·0	130	4(b)-4: 91·0	1039·0

(c) Load on wall=150 kg/m (polythene+stabilised soil roof)

	Wall design	No. of pillars	Cost (Rs)	Volume of non-lead bearing walls (cubic m)	Cost (Rs)	Load on foundation (kg/m)	Foundation option and cost (Rs)	Cost of wall+foundation (Rs)
3(d)	Masonry pillars at 2 m spacing	12	204·0	11·6	557·0	366	4(b)-4: 109·0	870·0
3(e)	Stone pillars at 2 m spacing	12	237·6	13·5	648·0	275	4(b)-4: 109·0	995·0
3(f)	Timber pillars at 2 m spacing	12	360·0	13·5	648·0	165	4(b)–4: 109·0	1117·0

(d) Load on wall=800 kg/m (soil roof)

	Wall design	Volume of walls (cubic m)	Cost of walls (Rs)	Foundation option and cost (Rs)	Cost of wall+foundation
3(a)	Burnt brick in mud	22·3	1403·0	4(a):594·0	1997·0
3(d)	Compacted soil block in mud	19·8	950·4	4(a):594·0	1544·4
3(c)	Stone in mud	29·7	2376·0	4(a):594·0	2970·0

Appendix 3. Stages 1 and 2. Roof covering and roof structure

Options 2(a) and 2(b) for the roof structure work out practically to the same cost, but the collar beam truss needs greater skill in execution. Hence option 2(a) is chosen for reliability considerations. Option 2(c) is the relevant structure for flat soil roofs. For thatch and Mangalore tiles, arecanut reepers are used in the structure. For the stabilised soil roof, split bamboo reepers (closely spaced) are used.

Design roof Load	Cost of roof covering (Rs)	Roof structure option	Details of structure	Cost of roof structure (Rs)	Total cost of covering + structure (Rs)	Load on walls (kg/m)
45 kg/m^2 (thatch)	100·00	2(a)	8 cm bamboo at 60 cm	150·00	250·00	60
100 kg/m^2 (Mangalore tile)	400·00	2(a)	10 cm bamboo at 60 cm	200·00	600·00	120
130 kg/m^2 (stabilised soil)	250·00	2(a)	10 cm bamboo at 45 cm	378·00	628·00	150
440 kg/m^2 (soil)	150·00	2(c)	3 timberlog 24 cm × 30 cm, 10 cm bamboo	640·00	790·00	800

Stages 1–2, and 3–4 may now be matched on the basis of the load transferred to the walls and the total cost arrived at for each roof covering. The final results are in table 1 and figure 5 of the text.

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